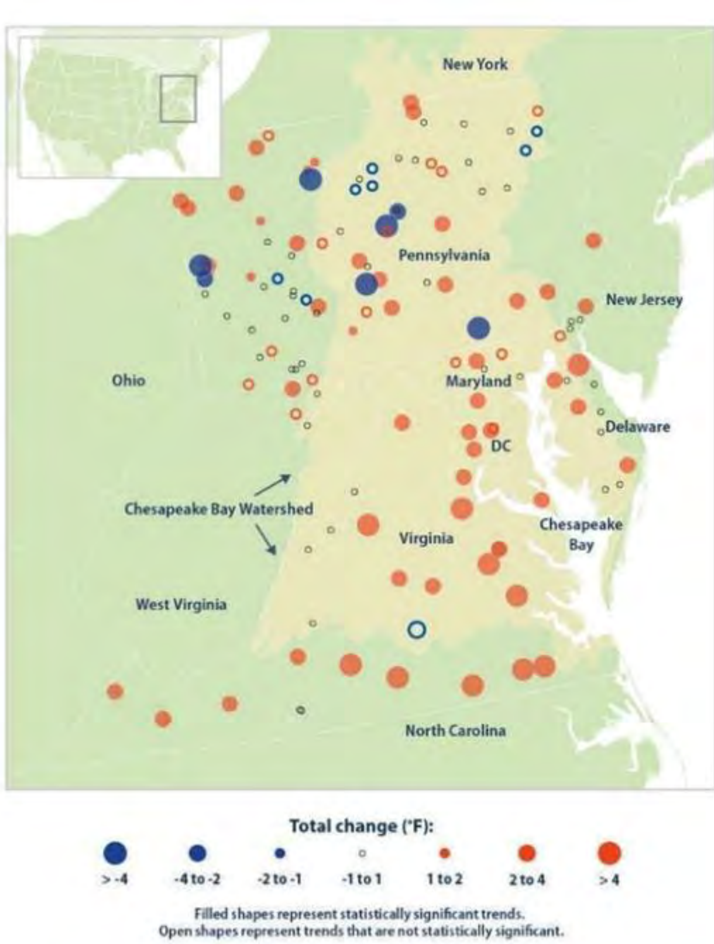
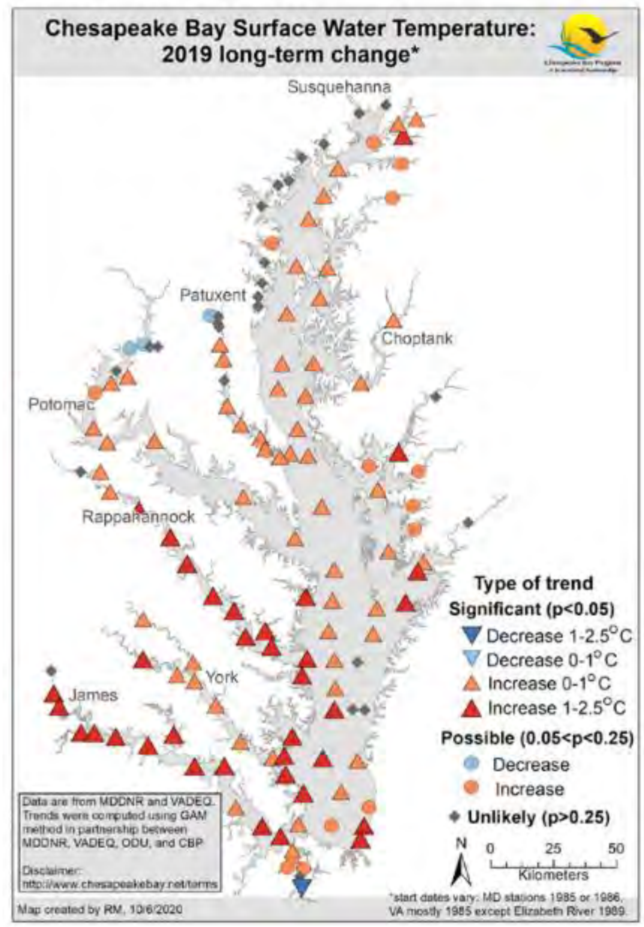
Rising Watershed and Bay Water Temperatures—Ecological Implications and Management Responses





A Scientific and Technical Advisory Committee Workshop Report

STAC Publication 23-001

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 1984, STAC has worked to enhance scientific communication and outreach through the Chesapeake Bay watershed and beyond. STAC provides scientific and technical advice in various 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.

Publication Date: January 20, 2023

Publication Number: 23-001

Suggested Citation: Batiuk, R., Brownson, K., Dennison, W., Ehrhart, M., Hanson, J., Hanmer, R., Landry, B., Reichert-Nguyen, J, Soueidan, J., Tassone, S., Vogt,B. 2023. Rising Watershed and Bay Water Temperatures: Ecological Implications and Management Responses – A STAC Workshop. STAC Publication Number 23-001. Edgewater, MD. (505 pages)

Cover graphic: Figure 1. Left. Changes in Stream Water Temperatures in the Chesapeake Bay Region, 1960–2014. Data source: Jastram and Rice, 2015. <https://www.epa.gov/climate-indicators/climate-change-indicators-stream-temperature> **Figure 2.** Right. Long term flow-adjusted trends in bottom water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019 from the Integrated Trends Analysis Team (ITAT). <https://www.chesapeakebay.net/who/group/integrated-trends-analysis-team>

STAC Administrative Support provided by:
Chesapeake Research Consortium
645 Contees Wharf Road
Edgewater, MD 21037
Telephone: 410-798-1283
Fax: 410-798-0816
http://www.chesapeake.org

Workshop Steering Committee:

Bill Dennison: Co-Chair, University of Maryland Center for Environmental Science; CBP Scientific, Technical Assessment and Reporting Team *(STAC Member)*

Rebecca Hanmer: Co-Chair, Chesapeake Bay Program Forestry Workgroup; USEPA Retired

Rich Batiuk: USEPA Retired; CoastWise Partners

Frank Borsuk, USEPA; Freshwater Fisheries Biologist

Katherine Brownson: U.S. Forest Service; CBP Forestry Workgroup

Matthew Ehrhart: Stroud Water Research Center; Member, CBP Citizens Advisory Committee

Scott Phillips: USGS; Co-Chair, CBP Scientific, Technical Assessment and Reporting Team

Julie Reichert-Nguyen: NOAA CBO; Coordinator, CBP Climate Resiliency Workgroup

Renee Thompson: USGS; Coordinator, CBP Healthy Watershed Goal Implementation Team

Bruce Vogt: NOAA CBO; Coordinator, CBP Sustainable Fisheries Goal Implementation Team

Workshop Project Team:

Anna Kasko: MDE
Anne Hairston-Strang: MD DNR
Bill Jenkins: USEPA
Britt Slattery: NPS; Fostering Chesapeake Stewardship GIT Coordinator
Brooke Landry: MD DNR; CBP SAV Workgroup
Breck Sullivan: USGS; STAR Coordinator
Carin Bisland: USEPA
Chris Guy: USFWS; Habitat GIT Coordinator
Chris Patrick: VIMS
Christine Conn: MD DNR
David Wood: Chesapeake Stormwater Network
Ed Dunne: DOEE
Gary Shenk: USGS
Gina Hunt: MD DNR
Jamileh Soueidan: Chesapeake Research Consortium
Jeremy Hanson: Chesapeake Research Consortium
Jessica Blackburn: Alliance for the Chesapeake Bay; CBP CAC Coordinator
John Clune: USGS
John Griffin: Chesapeake Conservancy
Jonathan Leiman: MDE
Judy Okay: J&J Consulting Inc.
Julie Mawhorter: USFS

Katie Ombalski: Woods and Waters Consulting
Kristin Saunders: University of Maryland Center for Environmental Science
Lew Linker: USEPA, CBP Modeling Coordinator
Lucinda Power: USEPA
Matthew Robinson: DOEE; Chair of CBP PPAT
Pam Mason: VIMS
Peter Tango: USGS; CBP Modeling Coordinator
Rebecca Golden: MD DNR
Sally Claggett: USFS
Sara Weglein: MD DNR
Stephen Faulkner: USGS
Tom Schueler: Chesapeake Stormwater Network

Acknowledgments:
STAC and the workshop steering committee would like to thank the following individuals for providing support in preparing for, during and after the workshop:

Meg Cole: CBP STAC Coordinator, Chesapeake Research Consortium

Amy Goldfisher: CBP STAR Staffer, Chesapeake Research Consortium

Alex Gunnerson: CBP STAR Staffer, Chesapeake Research Consortium

Hilary Smartwood: CBP WQ GIT Water Staffer, Chesapeake Research Consortium

Justin Shapiro: CBP Sustainable Fisheries GIT Staffer, Chesapeake Research Consortium

Sophia Waterman: CBP Environmental Management Staffer, Chesapeake Research Consortium

Table of Contents

Executive Summary

As atmospheric temperatures go up, water temperatures have been increasing in the Chesapeake Bay tidal waters and in streams and rivers across the Bay's watershed. Water temperatures are expected to continue rising, based on climate change projections.

Increases in water temperature have significant ecological implications for Bay and watershed natural resources and could undermine progress toward Chesapeake Bay Program (CBP) partnership goals for fisheries management, habitat restoration, water quality improvements, and protecting healthy watersheds. This STAC workshop examined current information on drivers and effects of rising water temperatures and sought answers to a critical question: what might the CBP partnership do now–within the scope of its current goals, policies and programs–to actively prevent, mitigate or adapt to some of the adverse consequences. Adapting to new water temperature conditions will have effects across the partnership.

Workshop preparation showed, from the outset, that the drivers, effects and likely management implications of water temperature increases are quite different between the Bay and the watershed. Therefore, both workshop days featured concurrent watershed and tidal sessions, and the findings and recommendations in the STAC report are organized in the same way.

Rising Water Temperatures in the Chesapeake Bay Watershed

* Water temperatures have been increasing in streams and rivers of the Chesapeake Bay watershed over the past several decades–even more than in the Bay's tidal waters. In many areas, water temperatures increased more than air temperatures, demonstrating that air temperature is not always the primary driver of water temperature in non-tidal waters.

* Land use has a significant impact on temperatures of stream flow and precipitation-induced runoff from land surfaces. Trees and riparian forests play a central role in stream temperature moderation, through shading, evapotranspiration and facilitating infiltration. Conversely, more developed areas with impervious surfaces contribute heated runoff to streams. Other landscape factors, like groundwater inputs, may help identify places that are more resilient to climate change to target for conservation, including healthy watersheds.

* Warmer water temperatures, including shorter-term extreme heat events, will negatively impact aquatic habitats and threaten many ecologically and economically important aquatic species. Stream temperature has direct and indirect effects on many biological, physical and chemical processes in the freshwater environment. Rising water temperatures may increase the occurrence or co-occurrence of known stressors (such as harmful algal blooms) that negatively impact aquatic species and habitats.

* "Cooling" best management practices (BMPs) such as riparian forest buffers, urban tree canopy and stormwater infiltration have the potential to mitigate rising water temperatures but overall, substantially more "heating" BMPs have been installed in the watershed. This suggests

that some practices implemented to improve water quality may be having unintended consequences for water temperature.

These findings and management implications led to the development of the following **recommendations** applicable to the lands within the Bay's watershed and its streams and rivers:

Coldwater Fisheries and Habitats: Chesapeake Bay Program partners need to accelerate conservation to protect the coldwater streams now supporting healthy aquatic life, especially native brook trout, which are extremely sensitive to rising water temperatures, and continue resiliency analyses and mapping to focus coldwater habitat restoration efforts.

Rural Waters and Habitats: In rural areas, CBP partners should work to strategically conserve and restore forests and aquatic habitats while promoting good agricultural stewardship practices that can reduce the amount of heated runoff being generated by farms.

Urban Waters and Habitats: In urban areas, CBP partners should increase tree canopy, vegetation and practices favoring infiltration to reduce the amount of heated runoff entering waterways, paying attention to under-served urban areas which historically suffer the worst heating and human health outcomes.

Best Management Practices (BMPs): The CBP partners should work to minimize the extent to which water quality BMPs are further heating waterways, and strategically use cooling BMPs to counteract the warming effects of climate change and land use where possible.

State Temperature Water Quality Standards: Given the vital role of Clean Water Act water quality standards (WQS in focusing federal, state, local and private actions to protect water quality and aquatic life. The Bay states and EPA should review and modernize the components of current WQS systems that would strengthen their capability to address climate-related rising water temperatures and drive area-targeted protection and restoration strategies.

Implementation actions and science needs are suggested in the report for each of these recommendations.

Rising Chesapeake Bay Tidal Waters Temperature

* Over the past three decades, the tidal water temperatures in the Chesapeake Bay have been increasing. These changes in tidal water temperatures are primarily driven by global atmospheric forcing (e.g., increasing surface air temperatures) and the warming ocean boundary.

* Rising water temperature in the Chesapeake Bay is already having an impact on many species and contributing to ecosystem regime shifts. Climate vulnerability scores and bay-specific research show a range of positive and negative responses of living resources to temperature and other climate change related factors.

* Positive impacts are likely for blue crab and some forage species (e.g. bay anchovy and menhaden), as warmer temperatures support higher productivity and increased habitat range as species move northward. However, shifts in predator distributions and diminishing seagrass habitat can have negative indirect effects on populations.

* Negative impacts are predicted for oysters due to their already depressed populations as a result of disease, overfishing, and habitat loss. While they can thrive in warmer temperatures, they are highly vulnerable to these stressors along with other climate-driven stressors, such as ocean acidification and changes in salinity driven by precipitation.

* Striped bass may experience both negative and positive effects from rising water temperatures at different life stages (larval to adult) and habitat use (rivers and estuaries to marine). While gradually rising water temperatures are important, other stressors (e.g., low water column dissolved oxygen that reduces the area of suitable habitat) and climate change consequences that exacerbate the exposure of species to heightened multiple stressors (e.g., increases in precipitation affecting nutrient loadings resulting in further decreases in dissolved oxygen, salinity fluctuations) and extreme events (e.g., increases in marine heat waves), are of great concern for maintaining populations in Chesapeake Bay.

* Without drastic improvements in water clarity or a reversal of warming trends, viable populations of eelgrass will likely be extirpated from Chesapeake Bay.

* Northward shifts in species ranges are being documented for several species. This is resulting in some Bay species shifting populations north while other species from the south are becoming more prevalent in the Bay. These shifts can result in changes to species abundance and distributions, food web dynamics, fishing behavior and the introduction of new fisheries.

* Likewise, habitats required by fish and shellfish species are shifting in range and experiencing impacts that lead to changes in fish abundance, distribution and reproduction success.

* Hardening of shorelines (use of bulkheads and rip rap) in response to shoreline erosion has negative impacts on fish communities and habitat, submerged aquatic vegetation (SAV), waterfowl, and water quality. Natural infrastructure provides ecosystem services in the face of climate change, including shoreline erosion protection, refuge of species from multiple stressors, including warmer temperatures, sedimentation mitigation, and improved water quality.

These findings and management implications led to the development of the following **recommendations** applicable to the Bay's tidal waters:

***Ecosystem-Based Management and New Temperature Regime*:**

- Establish Chesapeake Bay-wide striped bass fishing guidance based on temperature and dissolved oxygen thresholds to reduce catch and release mortality. Consider developing habitat condition thresholds and fishing guidance for other recreationally targeted species at risk during periods of poor habitat conditions.

- Develop and implement a strategy to improve communications between living resource managers, scientists and stakeholders on the new temperature regime, the impacts and management response/adaptation strategies.

- Hold a workshop with multiple fishery stakeholders to explore strategic, long-term ways to advance ecosystem approaches to fishery management in the Bay that incorporate climate change.

***Multiple Stressors*:** An interdisciplinary team of scientists, resource managers, meteorologists, and communicators should collaborate to design and create a publicly available marine heat wave alert system. Consider a marine heat wave indicator that incorporates dissolved oxygen and links to habitat preferences of key species such as striped bass, blue crabs, oysters, and SAV.

***Nearshore Habitat*:** Chesapeake Bay Program partners should develop common criteria and metrics to help target, site, design and implement tidal natural infrastructure projects in the nearshore where ecological and climate resilience benefits are highest.

Implementation actions and science needs are suggested in the report for each of these recommendations.

Across the Chesapeake Bay Watershed and the Bay's Tidal Waters…

There are significant gaps in understanding to be filled. The management recommendations are thus paired with recommendations for research, monitoring, modeling, and data analysis and interpretation. During the concurrent watershed and tidal sessions, the following common themes and linkages were identified:

- Modeling tool improvements: modeling at a finer scale, incorporating temperature change in our modeling systems, and improving the connections between models and monitoring of living resources is needed to better respond to rising water temperatures.

- Expanded monitoring: expanding monitoring networks to place more emphasis on tracking and better understanding water temperature change, and a focus on smaller streams, are necessary enhancements to the partnership's existing watershed monitoring network.

- Paired water and air temperature measurements: improving the ability to pair information about trends in water temperature with trends in air temperature at the appropriate scale will greatly improve understanding of the forces driving rising water temperatures and support management decisions.

- Nearshore research: improving understanding is needed on how and to what degree watershed BMPs can minimize warming for nearshore habitats of tidal tributaries in short to mid-term timeframes related to cooling benefits for SAV and fish.

- Thresholds: understanding threshold tolerance limits and communicating about the implications of thresholds to decision-makers and the public to improve understanding of why management tools and actions are needed to respond to rising water temperatures.

- Communication: communication with each other, with decision-makers, and with the public is key to ensuring that the implications of rising water temperatures are considered in decision making.

The CBP's management strategies and action plans for meeting the Program's goals in the 2014 Watershed Agreement need to take account of the fact that a critical, basic condition—water temperature—has been changing and will continue to do so. This STAC workshop was structured to initiate the full consideration of rising water temperatures in nearly every restoration, conservation, education and public communication decision—made individually as well as collectively—by the Chesapeake Bay Program partners. The recommendations include many actions which can be initiated in the near future, as well as actions in science, monitoring, modeling and program implementation which will help guide the Program in setting future goals.

1. INTRODUCTION

1.1 Workshop Goals, Objectives and Approach

Water temperature increases are occurring in Chesapeake Bay tidal waters and in streams and rivers across the Bay's watershed, and are expected to continue based on climate change projections. Water temperature increases have significant ecological implications for Bay and watershed natural resources, and could undermine progress toward Chesapeake Bay Program partnership goals for fisheries management, habitat restoration, water quality improvements, and protecting healthy watersheds. There is a critical need for insights into what the CBP partnership might do now–within the scope of its current goals, policies and programs–to prevent, mitigate or adapt to some of the adverse consequences. This STAC workshop was structured to help meet these needs through two primary objectives:

- Summarize major findings on the ecological impacts of rising water temperatures, including science-based linkages between causes and effects, on tidal and watershed living resources; and
- Develop recommendations on how to mitigate these impacts through existing management instruments, ranging from identifying best management practices to adapting policies and analytical approaches.

1.2 Management Relevance, Urgency and Outcomes

The impact of climate change on the restoration and protection of Chesapeake Bay and its watershed is being monitored, modeled and studied, and new knowledge is being gained. This workshop took advantage of available knowledge to determine how to better direct or redirect CBP partnership management instruments to help prevent, mitigate or adapt to harmful effects from water temperature increases. Examples of these management instruments include: (1) identification and better quantification of the benefits from temperature-lowering best BMPs for targeted implementation in the states' Phase III Watershed Implementation Plans (WIPs); (2) changes to habitat restoration strategies to mitigate or adapt to rising water temperatures; (3) adaptation of partnership and states to proactively respond to fisheries impacts associated with projected increases in watershed and Bay tidal water temperatures; and (4) enhancing the partnership's mapping and modeling tools to better evaluate where watersheds may be more vulnerable or resilient to stream temperature changes.

Previous STAC-sponsored and other scientific research and monitoring efforts have documented that water temperatures are rising and discussed the potential effects this could have on the Bay and its watershed (for example, Najjar et al., 2010). However, for nearly four decades, the CBP partnership has largely based its restoration and protection goals and decisions on assumptions of constant air and water temperature regimes. Further, the partnership has focused on nitrogen, phosphorus and sediment pollutant load reductions as the means to restore water quality and aquatic ecological integrity, with limited consideration of water temperature. Recently, the partnership has placed emphasis on possible impacts of climate-related changes, such as how BMPs might function in light of changing precipitation patterns, but not increasing water temperatures. So, there was a critical need for a STAC workshop focused on better understanding the potential effects of rising water temperatures and developing options to mitigate these effects.

This STAC workshop provided the ideal forum for: (1) updating information on the potential effects of rising temperatures; (2) improving understanding of the science-based linkages between causes and effects; and (3) using the enhanced scientific and technical foundations for recommending changes in partnership priorities, policies, and management decision support systems and tools. The findings and recommendations from this STAC workshop have provided the needed credibility for the partnership to fully factor increasing water temperatures into its decision-making for achieving the partnership's shared fisheries, habitat, water quality and healthy watersheds goals. To influence the states' implementation of the Phase III WIPs through 2025, stronger linkages between rising water temperatures and decisions about the selection and placement of BMPs must be forged now to change basinwide, regional and local decision-making in 2023-2025 and beyond.

Several participants in the workshop asked about including human health impacts that might be associated with water temperature rises -- issues such as the impact of heat-promoted harmful algal blooms on recreational use of tidal and non-tidal water, or effects on drinking water source supplies. Questions about how water temperature increases could affect human health-related water uses are clearly important to citizens, local governments, organizations and agencies, but they were beyond the scope of this STAC workshop.

1.3 Workshop Preparation and Planning

We addressed the workshop outcomes in three sequential phases, leading to production of the final workshop report.

Phase 1 This workshop preparation phase began with in-depth compilations of the CBP partners' and stakeholders' current understanding about Bay watershed and tidal water temperature increases, their ecological implications, any recognized temperature change thresholds, and current understanding of actions being taken to actively prevent, mitigate or adapt to rising water temperatures. The workshop's sponsoring committees, goal implementation teams (GITs), and workgroups were also challenged to initiate work on identifying a range of possible actionable recommendations to be considered and discussed at the workshops. For the first step in preparation for the two one-day STAC workshops, a series of nine synthesis papers and an addendum were prepared by teams of co-authors documenting the current state of knowledge of each of the topic areas to be addressed in the workshops (see Appendices D-M). In addition, the CBP Climate Resiliency Workgroup hosted a one-day working session in June 2021 devoted to a cross-workgroup review of our current level of understanding about rising watershed and Bay water temperatures (see Appendix U).

Phase 2 The first workshop was a full-day virtual meeting held on January 12, 2022. Concurrent tracks were designed to identify the ecological impacts and management implications of rising water temperatures on the watershed and tidal waters, respectively. This first workshop focused on building a more complete picture of interrelationships between the causes of increasing water temperature, the resultant ecological impacts, the range of management implications, and the relative scales of these causes and effects. For Day 1 plenary presentations, see Appendix Q; for links to recordings from Day 1, see Appendix R.

Phase 3 The third phase started with the STAC Workshop Steering Committee working from a synthesis of the first workshop to refine findings on the interrelationships and to develop draft recommendations for more effective use of the partnership's management instruments. The second workshop, one full-day virtual meeting held on March 15, 2022, focused on in-depth discussions to build consensus on the first workshop's findings and provide input on actions that the CBP partnership could take to address the impacts of rising water temperatures, capped off by a panel discussion among managers from across the partnership. Day 2 plenary presentations and links to session recordings can be found in Appendix Q and Appendix R, respectively.

1.4 Workshop Questions

The following questions drove the agendas for each of the one-day workshops based on parallel sessions focused on the watershed and the tidal waters issues:

Watershed Questions

- What do we know about what is driving rising water temperatures and what knowledge gaps do we need to fill before making management recommendations?
- What species and habitats are most vulnerable to the direct and indirect effects of rising water temperatures and what knowledge gaps do we need to fill before making management recommendations?
- What management actions are needed to address the known drivers and ecological impacts of rising water temperatures in coldwater, rural warmwater, and urban warmwater habitats across the watershed?
- How can state water quality standards be updated to better address rising water temperatures driven by land use and climate?
- Where are opportunities to better use or improve the Bay Program's existing monitoring programs and modeling tools to inform management decisions to address rising water temperatures?

Tidal Questions

- What are the direct and indirect positive and negative effects of rising water temperatures on the fishery and SAV resources?
- Are there certain effects more concerning than others from a resource management standpoint?
- What are the key factors to consider for the fishery/SAV resources to inform management action around these effects?

- How certain is our knowledge of temperature sensitivities on the fishery/SAV resources?
- What research gaps do we still need to fill to inform management action around temperature sensitivities (e.g., establishing temperature thresholds)?
- What temperature-specific analyses would be most useful for informing management actions for the fishery/SAV resource?
- Looking at the ecological effects, key factors to consider, and sensitivities related to rising water temperatures identified today, what are the management implications for the fishery/SAV resources?
- What management actions are agencies taking now or planning to address Bay water temperature change to the fishery/SAV resources?

1.5 Workshop Report

This workshop report is structured by focusing first on the effects of rising water temperatures in Chesapeake Bay's watershed followed by effects in Chesapeake Bay tidal waters. Within this workshop report, references to "watershed" means all the lands which ultimately drain to Chesapeake Bay and its tidal tributaries and embayment as well as free flowing rivers and streams. References to "tidal" mean all tidally-influenced waters within the Chesapeake Bay and its tidal tributaries and embayments and the adjacent shorelines. The separate focus on watershed and then tidal waters reflects the very different nature of the drivers behind the observed increasing water temperatures as well as the resulting effects on the living resources which depend on these free-flowing and tidally-influenced aquatic and estuarine ecosystems, respectively. These two separate sets of storylines, management implications and recommendations are then brought together in the context of a management perspective and a drawing out of commonalities between these two different ecosystems.

2. WATERSHED RISING WATER TEMPERATURES

2.1 What We Know: Watershed Storyline

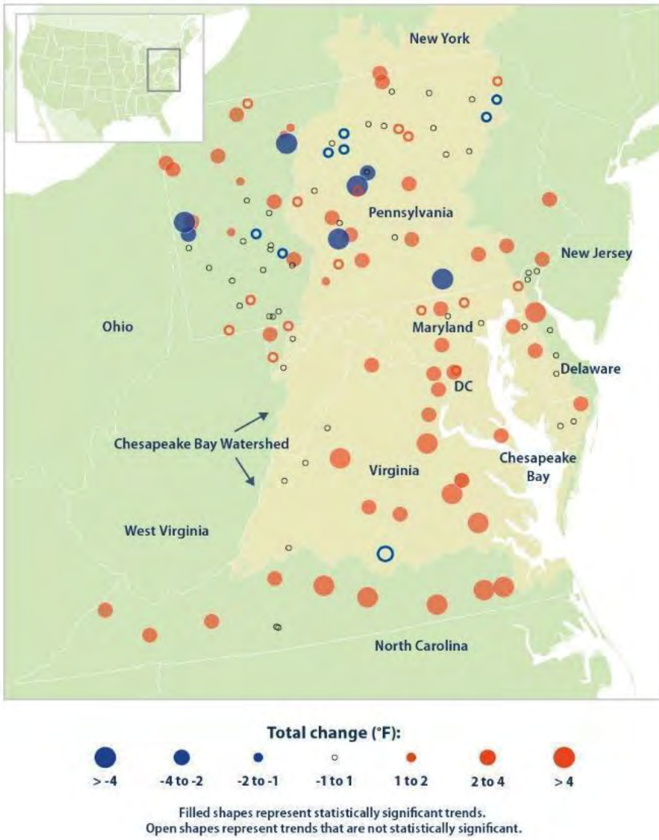


Figure 1: Changes in water temperatures in streams and rivers of the Chesapeake Bay watershed. Source: https://www.epa.gov/climate-indicators/climate-change-indicators-stream-temperature, based on data from Jastram and Rice, 2015

Water temperatures have been increasing in streams and rivers of the Chesapeake Bay watershed – even more than in the Bay's tidal waters. Furthermore, in many areas, water temperatures increased more than air temperatures from 1960 to 2010 in the Chesapeake Bay watershed (Rice and Jastram, 2015; Synthesis Element 5 Paper, Appendix I). This demonstrates that air temperature is not always the primary driver of water temperature in non-tidal areas (Figure 1). Air to water temperature ratios at sites show where land use or other factors are driving or buffering changes in water temperature.

Rising water temperatures can have major implications for stream ecosystems, local communities, as well as land and water management. Impacts on vulnerable coldwater species, such as the eastern brook trout, are of particular concern.

More robust data sets and methods should soon be available for evaluating annual and seasonal stream temperature trends (see for example Wagner et al. 2017). Stream ecosystems will likely be affected not only by longer-term stream warming trends, but also by shorter-term temperature events, including pulsed heat waves (see Tassone et al. 2022).

Drivers of Changes in Water Temperature

Changes in stream and river temperatures can be driven by rising air temperatures, but other drivers also have a strong influence. The workshop team developed a conceptual model summarizing the mechanistic drivers of non-tidal water temperature and their direction of influence (Figure 2). Negative arrows indicate drivers that can reduce water temperatures or provide a buffer against warming water temperatures. Positive arrows indicate drivers that can further exacerbate rising water temperatures. Many other interacting factors influence these broader drivers. A more detailed conceptual model is provided in the Synthesis Element 7/8 Paper, Appendix K. Land use, for example, has a significant impact on stream flow and runoff temperature, with riparian forest shade generally cooling streams relative to air temperature, while temperatures in streams receiving urban runoff from streets and other impervious surfaces may be higher than air temperature.

The relative importance of each driver will vary depending on the local landscape and the spatial and temporal scale of interest. Certain drivers will have a stronger influence either in the short or the long term, and certain drivers will have a more localized influence on water temperatures (i.e., channel buffering capacity), while others may have a broader influence on water temperature across the landscape (i.e., upstream land use). Additional work and site studies are needed to connect these mechanistic drivers with appropriate site- and area-specific information to inform management and land use decisions.

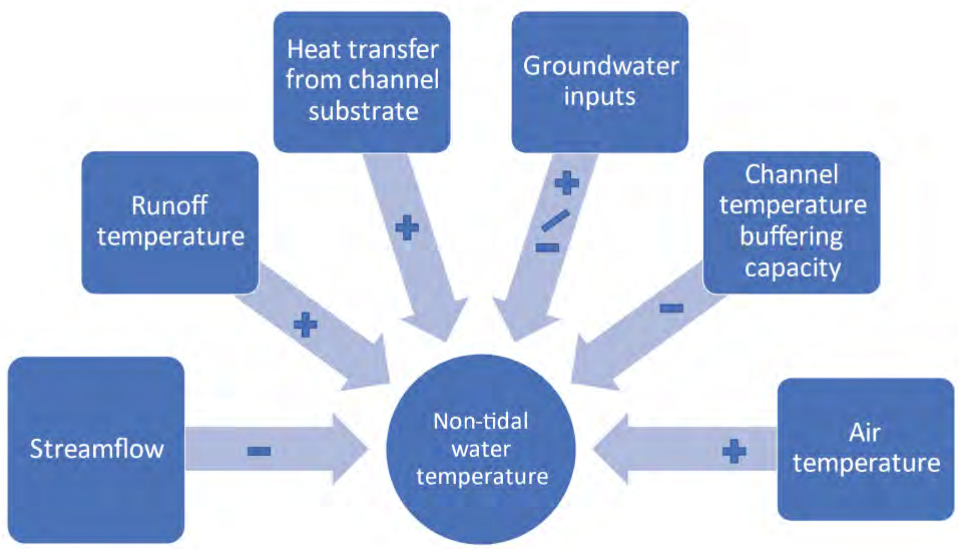


Figure 2: Major drivers of non-tidal water temperature and the direction of their influence. Source: Synthesis Element Paper 7/8, Appendix K.

During Day 1 of the workshop, participants were asked to rank the primary drivers in terms of their relative influence on water temperature and ability to influence the driver. Most of the drivers ranked highly in terms of their influence on water temperature (Figure 3). Runoff temperature, stream flow and channel buffering capacity were also identified as drivers that can be influenced through management. Other drivers, like groundwater inputs, may nonetheless be important to consider when identifying places and habitats that may be more resilient to climate change when targeting for conservation.

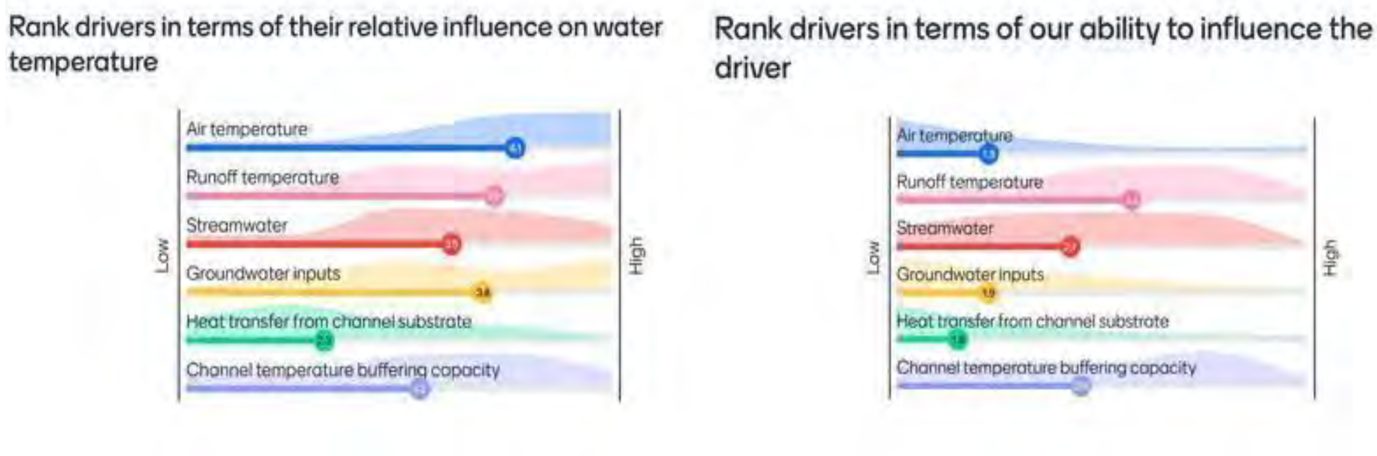


Figure 3: Left: Rankings from Workshop 1 participants (n=35) on the relative influence of each identified driver on water temperature. Rankings are on a scale from 0 (no influence) to 5 (very strong influence).
Right: Rankings from Workshop 1 participants (n=38) on our relative ability to influence each driver through management. Rankings are on a scale from 0 (no ability to influence) to 5 (very strong ability to influence).
For both figures: Circles represent the average ranking and the curves above each driver show the distribution of rankings.

Drivers of Rising Water Temperatures: Priority information needs

A key uncertainty is the degree to which various drivers and interactions between drivers influence water temperature in specific sub-watersheds. There is a need to invest in a strategically-designed stream temperature monitoring network that can answer the major questions about climate effects and other actions that influence water temperatures. Greater high-frequency or continuous water temperature monitoring is needed to better understand the relative local watershed/sub-watershed influence of various drivers as well as water temperature trends (including seasonal effects). State water quality standards monitoring strategies that focus on point source impacts may not be as useful for monitoring broader spatial and temporal trends. Additional monitoring is also needed at the air/water interface to identify hotspots where drivers are having a particularly large impact on water temperature as a way to target management. Finally, improved understanding of groundwater inputs is needed. Specific needs include better regional/sub-watershed models, more localized information about groundwater inputs, and a better understanding of how climate change could impact groundwater inputs.

Ecological Implications of Rising Water Temperatures

The workshop team adapted a high-level conceptual model of freshwater resource vulnerability from Foden et al. (2013) (Figure 4). This biophysical model does not include resource management considerations, such as the costs associated with protecting species or habitats. The

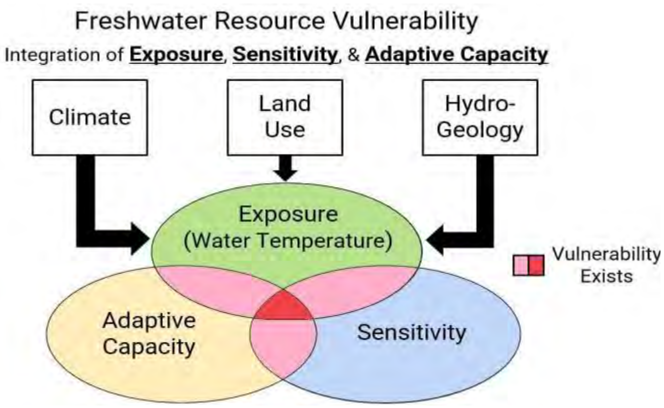


Figure 4: Conceptual model of freshwater resources vulnerability, Source: Foden et al. 2013.

model integrates a species or a habitat's vulnerability based on its **exposure** to rising water temperature, its **sensitivity**, as well as its **adaptive capacity**.

Warmer water temperatures will negatively impact aquatic habitats and threaten many ecologically and economically important species. Stream temperature has direct and indirect effects on many biological, physical and chemical processes in the freshwater environment, including significant impacts on fish metabolism, physiology and behavior, as referenced in the non-tidal fisheries and stream health paper, Synthesis Element 1Paper (Appendix D). It is expected that the strongest negative species-level impacts will be on coldwater species (e.g., eastern brook trout *Salvelinus fontinalis*) due to their exposure and sensitivity to rising water temperature. However, watershed-wide, warmwater aquatic species are most common. Although more tolerant to temperature increases, they are sensitive to extreme temperatures (see ORSANCO *Temperature Criteria Re-evaluation* 2005 in Synthesis Element 1 Addendum, Appendix E) and to indirect effects of higher temperatures, such as lower dissolved oxygen concentration and competition with non-native species.

Workshop participants were asked to rank eight species in terms of their relative exposure and sensitivity to rising water temperature. Participants observed a positive relationship between a species' perceived exposure to rising temperature and a species' sensitivity to rising temperature. Brook trout and checkered sculpin (coldwater species) were ranked the most exposed and sensitive to rising water temperature.

Brook trout are an essential part of the headwater stream ecosystem, an important part of the upper watershed's heritage (the freshwater state fish of Virginia, West Virginia, Pennsylvania and New York), and a highly-prized recreational resource. Synthesis Element 1 reviews models developed to predict stream temperatures and brook trout occupancy, and first-cut predictions are dire for occupancy impact as water temperatures rise (Appendix D). However, the paper points out factors that can mitigate the impact and response of streams to increases in air temperature, such as land use, landform features and fine-scaled groundwater inputs. Cold groundwater input increases a stream's capacity for supporting coldwater fisheries.

Fine-scale analysis is required to identify patch/catchment characteristics and their interactions on thermal resiliency. Site-specific data are needed on local groundwater inputs to identify streams that may be particularly vulnerable or resilient to warming surface water temperatures. Protecting native brook trout habitat and the contributing watersheds/sub-watersheds thus requires protection/restoration strategies at the patch scale.

Spatial characteristics also influence exposure to rising water temperatures. These include cross-sectional features of the stream channel, aquatic connectivity, and landscape features, and whether there are accessible thermal refugia during extreme heat events, can also influence exposure to rising water temperatures. In general, waterways with low-forested watershed cover, sparse riparian cover, and heated urban runoff are particularly vulnerable to warming.

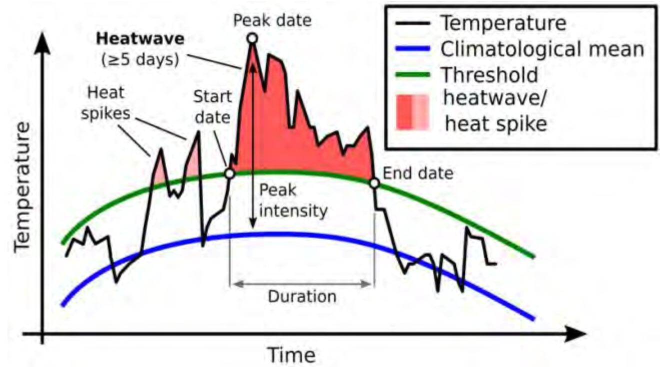


Figure 5: Characteristics of aquatic heatwaves. Source: Hobday and others 2016.

The ecological impacts of rising water temperature are influenced by specific ways in which temperature is warming. Shifts in seasonality (e.g., warmer winters, shift in season length) may impact spawning timing or migration which could influence exposure to rising water temperature. Pulsed extreme warmwater events (i.e., heatwaves) have a disproportionate impact on the environment relative to long-term changes in mean water temperature (Figure 5). Aspects of aquatic heat waves that are likely to affect vulnerable species include heat-wave frequency (i.e., the number of heatwaves per unit time), duration (i.e., the amount of time a heatwave lasts), intensity (i.e., how hot a heatwave gets), and onset rate (i.e., how quickly temperature reaches peak intensity).

Rising water temperatures may increase the occurrence or co-occurrence of known stressors that negatively impact aquatic species and habitats. Water temperature is a catalyst for biochemical reactions that negatively impact habitat quality at high water temperatures. Some known stressors that occur as temperature increases include:

- Low dissolved oxygen: gas solubility decreases with increasing water temperature (warm water holds less oxygen than cooler water).
- Invasive species: warmwater species have a longer time period in which to expand to inhabit new habitats to which they are not native.
- Algal blooms: cyanobacteria are known to perform well with elevated water temperatures and can develop into harmful algal blooms producing toxins.
- Bacterial/viral outbreaks: warm water increases physiological stress making it harder for species to fight off infection.
- Distribution and toxicity of other pollutants (e.g., heavy metals, pesticides, ammonia, etc.): rising water temperature mobilizes and increases the toxicity of other pollutants.

Increasing water temperatures will likely alter ecosystem structure and function. For example, aquatic ecosystems may move from diatom dominated to green-algae or cyanobacteria dominated. This alteration would represent a shift towards less nutritious food sources. In headwater streams, macroinvertebrates may also shift from coldwater sensitive fauna to more tolerant taxa and force changes in foraging behavior of fishes that rely on these communities as primary food sources.

Increasing water temperature will further isolate coldwater populations while expanding the range of warmwater and non-native species. As novel communities interact, there will be shifts in predator/prey interactions that are likely to alter energy and nutrient flow.

Priority information needs

Temperature effects on freshwater fish have been studied over many years, across a range of different aspects (e.g., lethality, reproduction, physiology), and these studies have been used to develop federal temperature criteria used in state water quality standards. Even so, there is more to study on impacts of elevated temperature, especially to non-trout species, including lower parts of the food web such as algae, biofilms, zooplankton, and macroinvertebrates. Management strategies would benefit from greater information on impacts of elevated temperature on species life stages, predator/prey interactions, and how these interact with multiple stressors. High-frequency (sub-daily) monitoring is needed to understand which places are most exposed and sensitive to pulsed heating events such as heatwaves.

2.2 Management Implications of Rising Water Temperatures

Multiple policies and practices could be considered to address the drivers of rising water temperature and ecological implications. These include policies that promote the protection and maintenance of natural lands that provide cooling benefits, including forests, wetlands and healthy watersheds. They also include BMPs included in jurisdictions' Watershed Implementation Plans (WIPs) and habitat restoration strategies.

Trees matter. By shading, cooling (evapotranspiration) and facilitating infiltration of rainwater, forests, riparian forest buffers and urban tree canopies play a central role in moderating the ecological risks of rising temperatures. CBP goals and practices for increasing riparian forest buffers, urban tree canopy and forest conservation are all relevant and could be reinforced.

Conserving existing healthy watersheds can help promote resiliency to rising water temperatures. Key factors of healthy watersheds that may moderate rising temperatures include:

- Land use/land cover: percent forest cover (catchment and riparian), percent natural land cover.
- Hydrology/flow alteration, including infiltration rates of land use/land cover types.
- Underlying geology/groundwater interaction.

Promoting practices that maintain or increase forest and natural land cover types, reduce flow alteration of streams, and are strategically sited based on an understanding of underlying geology and groundwater recharge can increase resiliency to rising water temperatures. Watershed characteristics and landscape factors that influence vulnerability and resilience to rising temperatures are reviewed in the watershed health paper, Synthesis Element 4 (Appendix H).

Some BMPs have the potential to mitigate rising water temperatures, but watershed-wide, there has been substantially greater implementation of "heater" BMPs as compared with "cooler" BMPs. BMPs can influence water temperature by impacting multiple drivers of water temperature identified in the conceptual model. The workshop team conducted a synthesis effort evaluating the temperature impacts of Bay Program BMPs and grouped BMPs based on the strength and direction of their impact on water temperature. **"Heaters"** include stormwater retention ponds, floating treatment wetlands and vegetated open channels. **"Coolers"** include riparian forest buffers, upstream tree planting, urban stormwater infiltration, and wetlands restoration, enhancement and rehabilitation. Many BMPs were classified as either "uncertain" or "thermally neutral".

In many years, there have been approximately three times (3x) as many heater BMPs as there were cooler BMPs implemented, suggesting that some of the practices being implemented to improve water quality may be having adverse, unintended consequences for water temperature (Figure 6).

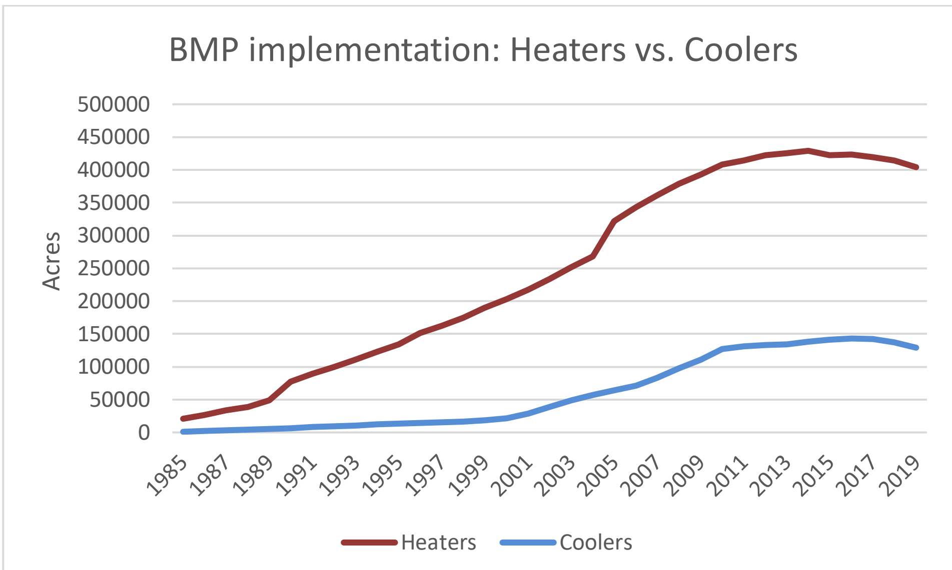


Figure 6: Trends in implementation of BMPs that may be having adverse impact on water temperature.

2.3 Management Recommendations

Initial management recommendations were drafted by the Workshop Steering Committee's watershed project team subgroup based on the Synthesis Papers and input received during Workshop 1. These initial recommendations were presented to Workshop 2 participants for discussion, and their input was solicited during breakout groups. The watershed project team then further refined the management recommendations based on the input received during Workshop 2.

The management recommendations, implementation actions and science needs below are grouped into three fisheries and habitat categories—Coldwater, Rural and Urban, and two cross-cutting subjects—Best Management Practices and Water Quality Standards. Why separate Coldwater from other Rural fisheries and habitats? It is to signal the differences in the types and intensity of measures required to sustain the highly temperature-sensitive, and treasured, coldwater species such as brook trout. Rural and Urban habitats have their own distinctive challenges and opportunities to address the aquatic ecosystem effects of rising temperatures.

Coldwater Fisheries and Habitats Recommendation

Recommendation 1: *Chesapeake Bay Program partners need to accelerate conservation to protect the coldwater streams now supporting healthy aquatic life, especially native brook trout, which are extremely sensitive to rising water temperatures, and continue resiliency analyses and mapping to focus coldwater habitat restoration efforts*

Rationale: Even though the CBP partnership is committed to brook trout stream protection and restoration, suitable brook trout habitat is still diminishing, due to development impacts such as heated stormwater runoff and especially loss of riparian forest. Stream temperature warming increases the urgency to identify the best habitat for land conservation and other restoration actions, and there are excellent mapping tools for habitat identification. More data are needed on local groundwater inputs to identify streams that may be particularly vulnerable or resilient to warming surface water temperatures.

Workshop participants were briefed on Maryland's "Conservation Framework for Increasing Resiliency for Maryland's Brook Trout". Success factors in the strategic framework included: (1) use of scientifically-valid, standardized survey and assessment techniques statewide; (2) choosing watersheds for resiliency and directing protection and restoration projects to those that provide the greatest opportunity for brook trout persistence into the future (including genetic diversity); and (3) working closely with partners to review stormwater infrastructure, construction and habitat projects that might impact coldwater resources (Goetz, 2022).

Workshop participants discussed opportunities to use conservation, restoration and BMPs to minimize stream warming in these important habitats. For example, where there are farms in these watersheds, partners should prioritize working with agricultural producers to minimize the potentially adverse impacts of agricultural practices to stream temperatures. Likewise, nonproductive agricultural lands and former minelands can be reforested to increase groundwater infiltration and forested cover in priority watersheds.

Based on years of study and coordination, e.g., through the CBP Brook Trout Workgroup, partner biologists and program leaders know what needs to be done and in what locations to protect coldwater habitats. Rising temperatures increase the urgency of connecting the science to the decision-makers at the federal, state and local levels so that effective conservation and restoration strategies can be coordinated across the relevant entities, adequately funded, and implemented.

Implementation Actions:

1. Partners should prioritize protecting currently forested watersheds containing high quality coldwater habitat, with land conservation practices (i.e., fee-simple purchase, conservation easements, open space programs, etc.).

2. Riparian forest buffers should be maximized in all coldwater watersheds. CBP partners should build on and intensify their existing strategies for conservation and restoration of riparian forest buffers and find new public-private funding.

3. Each state should develop a strategy that pulls federal, state (e.g., departments of environment, transportation), private, non-governmental organization (NGO), and landowner resources together for coldwater conservation partnerships. State frameworks like Maryland's might be used to identify "best of the best" watersheds and incentives given to local governments to promote and maintain these watersheds as a historic, scenic and recreational priority.

4. Promote good agricultural stewardship, to include increased use of cooling BMPs, to minimize the impacts of agricultural land use in watersheds with high quality coldwater habitat. Enlist the federal and state partners in the CBP's Agriculture and Forestry Workgroups.

5. In priority coldwater habitat areas for conservation and restoration:
    a. Develop stronger engagement with private landowners, including working with agricultural agencies to promote cooling practices, and improving conservation easement programs and incentives.
    b. Work with local governments to improve land use planning and evaluation of development projects in high quality habitat areas and to better utilize new and existing programs for protecting their coldwater fisheries.

6. Within the strategic framework for identifying potentially resilient streams for restoring coldwater habitat, implement habitat restoration in degraded landscapes, including the reforestation of abandoned minelands and the restoration of degraded streams to improve connectivity and expand available habitat, while minimizing the loss of mature riparian trees

Science Needs to Support Implementation: Increased continuous, high-frequency surface water temperature monitoring in headwater (i.e., coldwater) streams will help to identify and prioritize waterways for restoration and conservation. Likewise, implementing sediment/benthic temperature monitoring along with groundwater mapping will help determine which waterways are most resilient to warming and provide the greatest opportunity for brook trout persistence in the future. Lastly, longer-term temperature and brook trout monitoring will provide richer insights into factors contributing to restoration and watershed conservation success.

Rural Waters and Habitats Recommendation

Recommendation 2: *In rural areas, CBP partners should work to strategically conserve and restore forests and aquatic habitats while promoting good agricultural stewardship practices tha t can reduce the amount of heated runoff being generated by farms.*

Rationale: Rural landscapes are highly variable, providing important lands and waters for agricultural production, habitat and communities. Given this variability, an equal level of effort won't always lead to equal outcomes for stream temperature in different landscapes. A strategic approach to conserving and restoring forests and aquatic habitats will ensure that resources are spent in the places and on the practices that will have the greatest benefits for cooling waterways. Riparian forest buffers are essential for cooling waterways. However, considering the width of affected streams and rivers and the potential for heated water flows to bypass buffers, riparian buffers will only accomplish so much, and other upstream practices are needed to minimize stream warming.

On agricultural lands, the CBP partners have generally focused on practices that reduce nutrient and sediment loads. Unfortunately, some management practices such as farm ponds can contribute to stream warming. Workshop participants discussed difficulties that farmers might have avoiding all use of practices that add to heated runoff, and concluded that strategic whole-farm planning could help ensure that sufficient cooling practices are utilized to minimize trade-offs between water quality and water temperature.

At the same time, the CBP partners should work to strategically restore aquatic habitats to minimize the impacts of warming temperatures on aquatic biota and ecosystems. For example, there are opportunities to improve aquatic connectivity between suitable habitat patches that could improve access to thermal refugia during peak summer water temperatures. Workshop participants were shown an example of a very "restorable" stream reach in Pennsylvania, just downstream from a forest-buffered coolwater stream area, where installing forest buffers could extend the healthy aquatic habitat conditions. Note that the aquatic habitat restoration concepts discussed in this part of the workshop were measures to prevent and offset thermal impacts on aquatic biota. Participants commented at several points of the workshop on the need for such measures (e.g., riparian shading, thermal refugia) to be incorporated into stream restoration BMPs now being implemented by the CBP partners for nutrient and sediment reduction.

Implementation Actions:

1. Improve and conserve forest cover throughout the landscape, ensuring rivers and streams are well buffered. Improving forest cover includes both reforesting upland areas as well as improving management of existing forests to encourage better infiltration and improve forest resiliency (for example, by increasing forest age class diversity). A strategic approach could prioritize areas where there is the greatest opportunity for conservation such as healthy coolwater streams, areas downstream of intact coldwater habitats, and streams that have a significant opportunity for ecosystem recovery based on restoration efforts. The Forestry Workgroup could work with the Chesapeake Conservation Partnership, the Chesapeake Bay Program Office (CBPO) GIS team and/or contractors to identify locations in need of reforestation or improved forest management to cool waterways.

2. Use the improved Bay watershed mapping capability to prioritize specific stream reaches where riparian buffer plantings can exert the greatest cooling impact in rural watersheds. The Forestry Workgroup could work with the CBPO GIS team and/or contractors to

develop a RFB priority map for stream cooling. The CBP promotes RFBs everywhere in the watershed because of their nutrient and sediment reduction benefits. Stream temperature regulation is an additional high value benefit.

3. Use aquatic habitat restoration to improve connectivity between suitable habitat patches and improve access to thermal refugia. The Stream Health Workgroup could help develop design guidance for restoration practitioners that would improve the benefits of restoration for buffering aquatic biota from the impacts of aquatic heatwaves.

4. Improve technical assistance and programs available to private landowners to support forest land conservation, tree planting, and better whole farm planning, including a focus on agroforestry, improving soil health and infiltration as well as other practices that prevent heated runoff from reaching the riparian corridor. Natural Resources Conservation Service (NRCS) and the Agriculture Workgroup could help support efforts to integrate considerations of rising water temperatures into USDA's work to support farmers in implementing climate-resilient farming practices.

5. Incorporate rising water temperatures in CBP partner strategies for working with local governments —for example, modification of codes and laws where appropriate to encourage conservation BMPs and cooling practices and the lessening of impervious surfaces where development of rural areas is proposed. The Local Leadership and Communications Workgroups at CBP could help develop tailored communications materials for local governments to help improve understanding of the implications of rising stream temperatures and examples of effective local actions that could help mitigate these impacts.

Science Needs to Support Implementation: In rural areas, there is a need for targeted research in small agricultural watersheds to measure temperature impacts of agricultural land and water management practices, including infiltration practices, when implemented on a large scale. There are also opportunities to further investigate the efficacy of other cooling mitigation strategies, including wetland creation, dam/pond removal, floodplain restoration, beaver analogue projects, and improved roadside ditch management. Finally, the CBP partners could use the new high-resolution land use data to determine the maximum rural stream mileage available for forestation and develop models to determine whether the installation of future stream "cooler" and "shader" practices will mitigate watershed warming factors.

Urban Waters and Habitats Recommendation

Recommendation 3: *In urban areas, CBP partners should increase tree canopy, vegetation and practices favoring infiltration to reduce the amount of heated runoff entering waterways, paying attention to under-served urban areas which historically suffer the worst heating and human health outcomes.*

Rationale: Urban rivers and streams tend to be particularly vulnerable to the effects of stream warming, as the loss of natural cover and prevalence of impervious surfaces increases the volume and temperature of runoff entering waterways. At the second workshop, participants mentioned several studies that documented increases in urban stream temperatures. One study–Nelson and Palmer (2007)–showed that after summer rainstorms in the Anacostia watershed, urban runoff resulted in increasing stream water temperatures by about 3-4 degrees Celsius. The pulses of warmer water lasted about three hours in the receiving stream system (Synthesis Element 7/8 Paper, Appendix K).

Workshop participants agreed that significant urban water temperature increases and impacts on stream biota are a predictable outcome of observed increases in urban heating, but as monitoring water temperature has not been a recent priority, site-specific information is lacking.

Heated impervious surfaces play the primary role in heating stormwater runoff, but some of the BMPs used to reduce nutrient and sediment loads in urban areas, such as stormwater detention ponds, can also warm surface runoff. To minimize these trade-offs between water quality BMPs and water temperature, the CBP partners should identify opportunities to further incentivize the use of BMPs that provide cooling benefits over the use of BMPs that add heat to waterways.

"Cooling" BMPs include tree planting to increase urban tree canopy, lawn conversion and forest buffers along urban waterways. Stormwater management practices that facilitate infiltration of rainwater into soil (bioretention, porous pavement, and infiltration practices without underdrains) are also cooling BMPs as infiltrated stormwater is not further heated by impervious surfaces. Stormwater infiltration BMPs are encouraged by EPA and the jurisdictions, and increasingly adopted. District of Columbia participants in the workshop pointed to (limited) research that has measured stormwater cooling in bioretention installations.

Stormwater infiltration BMPs are not "refrigerators," and generally cannot compensate for the effect of impervious surfaces on stream temperatures. Both stormwater management infiltration practices and expanded urban tree canopy have been promoted by the CBP partners for nutrient and sediment reduction, and it makes sense to couple these measures for urban cooling as well.

Practices that increase urban tree canopy also provide myriad other benefits to urban communities, including cooling air temperatures and improving air quality. Where possible, Bay Program partners should use existing environmental justice and equity mapping tools to identify locations where implementing these practices could be particularly beneficial to historically under-served populations. Bay watershed cities have already begun "tree equity" initiatives to cool hot neighborhoods, and these could be linked to stream cooling measures.

There is tremendous variability across developed areas in the Chesapeake Bay watershed, ranging from small townships to large metropolitan areas with varying hydrology, soil conditions, and proportions or types of impervious and pervious cover. For urban areas adjacent to wider rivers and waterways, it may be more difficult to directly cool these waterways with forest buffers. In these places, partners could identify opportunities to create thermal refugia or improve access to thermal refugia through in-stream and riparian habitat restoration work. Where stream restoration BMPs are installed for sediment and nutrient removal (bank and instream modifications), participants said that removal of existing riparian canopy coverage should be minimized so as to maintain cooling benefits already present.

Stormwater runoff for some areas will be captured by combined stormwater and sewage systems, while most areas have separate storm sewers and sanitary sewage lines. The cooling or heating impact of combined versus separate sanitary sewer systems was not studied but is worth further exploration. In areas with combined sewer systems, there are often initiatives to promote green stormwater infrastructure that can lower the volume and temperature of runoff that enters the system.

Another important factor that arose in workshop discussions was the intersection of human health impacts and rising water temperatures. Urbanized areas often have areas with legacies of toxic pollution from industrial or other sources, and these legacies can have lasting impacts on local soils or waterways depending on the pollutant and its ecotoxicity pathways. Bacteria and harmful algal blooms are also relevant human health concerns for numerous waterways. Water temperature can influence these pollutants, how they move through the ecosystem, and how they ultimately impact aquatic biota and human health. These human health concerns are doubly important when considering the disproportionate historical and continued impact of pollution on under-served communities of color.

Rising air and water temperatures increase the urgency of broadly implementing several goals and programs which the CBP partners have adopted – use of "green technology" infiltration methods for controlling stormwater from developed land uses, achieving a net gain in urban tree canopy, and promoting "Bay friendly" and native landscape planting in urban and suburban areas.

Implementation Actions:

1. Decrease the amount of turf in urban and suburban areas, using lawn conversion programs to increase rainwater infiltration capacity, shading trees and shrubs, and use of native plants.

2. Encourage the retention and expansion of urban tree cover (both in the riparian zone and upstream), especially in under-served urban areas which historically suffer the worst heating and human health outcomes. Strengthen implementation of the CBP's Urban Tree Canopy strategy.

3. Use aquatic habitat restoration to improve connectivity between suitable habitat patches and improve access to thermal refugia. The CBP Urban Stormwater Workgroup could add guidance on how to consider water temperature effects and thermal refugia to its stream restoration BMP protocols.

4. Emphasize the multiple benefits of cooling BMPs such as urban trees (e.g., air quality, public health, urban livability) to better communicate about these practices with residents and local governments and to access additional sources of funding.

Science Needs to Support Implementation: For urban areas, the most significant science needs are to better understand how rising water temperatures interface with social science or public health issues, especially among under-served residents. Examples include evaluating the impacts of heated runoff and pollution concerns stemming from direct or indirect effects of elevated water temperature. An emphasis on improved understanding of locally relevant co-benefits for BMPs and restoration projects is also a priority science need.

Best Management Practices (BMPs) Recommendation

Recommendation 4: *The CBP partners should work to minimize the extent to which water quality BMPs are further heating waterways and strategically use cooling BMPs to counteract the warming effects of climate change and land use where possible.*

Rationale: Certain water quality BMPs are known to warm surface water temperature, including wet ponds, detention ponds, farm ponds and confined animal feeding operation (CAFO) lagoons. While these practices may be very effective and necessary to achieve nutrient and sediment load reductions, they may be having unintended consequences for water temperatures and stream ecosystems. There are other BMPs that can either directly cool waterways (i.e., riparian forest buffers) or can help minimize further stream warming (i.e., infiltration and bioretention practices).

The greater use of heating BMPs over cooling BMPs in the Bay watershed suggests a need to focus on incorporating temperature considerations into BMP selection and design.

The following actions are addressed to the CBP Goal Implementation Teams and workgroups responsible for providing guidance on BMPs, and to the multitude of local, regional, state and federal agencies and partners implementing them through the jurisdictions' WIPs.

Implementation Actions:

1. Work with local governments to avoid using "heater" BMPs near streams and identify opportunities to incentivize stacking multiple stormwater "cooler" BMPs over "heater" BMPs. Coldwater habitats are particularly sensitive and warrant extra protection.

2. For practices with the potential to exacerbate stream warming, develop specific design recommendations and criteria, taking landscape characteristics into account, to minimize warming impacts.

3. Relevant regulatory and stormwater permitting agencies should collaborate to review existing design criteria for new stormwater and restoration practices installed in cold and cool-water watersheds to avoid further stream warming.

4. For cooling practices whose efficacy is likely to be impacted by climate change, provide design recommendations to ensure these practices will remain resilient to likely future climate scenarios. This could include updating forestry BMP plant lists to make sure the appropriate species are being planted, accounting for local conditions, species

characteristics, and future hardiness zones in the warming watershed, and encouraging diversity in plant selection to hedge against potential losses to invasive pests and plants.

5. Where heating BMPs are needed to effectively address water quality concerns (no suitable cooling BMP alternatives are available), take a whole farm, whole property or whole landscape approach to ensure that enough cooling BMPs are implemented to offset any warming attributable to heating BMPs. Treatment trains should be used where possible to maximize infiltration and minimize heating.

Science Needs to Support Implementation: While the temperature effects of certain BMPs are well understood, at least in general terms, there are many BMPs where the CBP partners do not currently have a good understanding of temperature effects (for example, stream restoration, agricultural BMPs and wetlands BMPs). There is a need for a more robust assessment of which BMPs are heaters and coolers and to what extent. This could involve using a systematic expert elicitation process to better identify the BMPs likely to influence water temperature as well as the direction and magnitude of the temperature impact. Targeted research efforts should also further evaluate how various landscape characteristics, including groundwater, groundwater-surface water interactions, soil characteristics—both physical and chemical—underlying geology and land cover, mediate the temperature effects of BMPs and the scale at which various BMPs need to be implemented to have a measurable impact on water temperature.

State Temperature Water Quality Standards Recommendation

Recommendation 5: *Given the vital role of Clean Water Act water quality standards (WQS) in focusing federal, state, local and private actions to protect water quality and aquatic life, the states and EPA should review and modernize the components of current WQS systems that would strengthen their capability to address climate-related rising water temperatures and drive targeted protection and restoration strategies.*

Rationale: All CBP jurisdictions have a "water temperature policy" in their temperature WQS, but it needs to be updated to deal with climate-related water warming (Addendum, Appendix E). For decades, the standards (temperature criteria, monitoring schemes) have protected aquatic life and other water uses from heated discharges (e.g., power plants). Maryland officials showed the second workshop participants how they intend to use temperature WQS to drive better protection of trout streams from impairments caused by climate and land use impacts. The state added a forest buffer (shading) provision to its temperature criteria and is working on TMDL options. Workshop participants noted expert advice that current temperature criteria to protect aquatic life from heat discharges ("dots on the landscape") may not be protective for climate-related heating. Current monitoring regimes to detect impacts of discrete point sources need to be re-designed for climate-related heating. Participants had ideas for how to get started on the WQS modernization process. Just as the states' Chesapeake Bay WQS focused restoration action through the Chesapeake Bay TMDL and state WIPs, the states and EPA can work together to update the WQS mechanisms related to temperature, taking advantage of a large body of temperature-related fisheries research and advice from experts throughout the US.

Implementation Actions:

1. Convene EPA and jurisdiction WQS and 303(d) practitioners to explore how to make Chesapeake Bay watershed WQS effective to combat rising water temperatures. Evaluate accuracy of aquatic use zones (e.g., coldwater, coolwater, warmwater fisheries); refinement of temperature criteria for fisheries (e.g., to protect growth and reproduction) and corresponding biological criteria; monitoring/analysis methods and strategies adapted to climate-related temperature changes, taking into account land use influences and groundwater inputs. Evaluate TMDL options to spur restoration of temperature-impaired water uses. Can anti-degradation policies be leveraged to increase protection of current high-quality waters, especially healthy native trout streams? Aim to complete this evaluation in 12 months, building in advice from experiences elsewhere in the U.S.

2. Based on this evaluation, develop a plan to "modernize" these Clean Water Act tools to improve jurisdictions' capability to protect indigenous (and naturalized) populations of coldwater, coolwater and warmwater aquatic life from climate-related water temperature increases. The timing for making regulatory changes could be based on the regulatory WQS triennial review process.

3. Improve interstate cooperation and effectiveness by leveraging the CBP to promote information-sharing, problem-solving, and monitoring support.

4. Stronger anti-degradation measures could improve protection of temperature-threatened high-quality waters, e.g., native trout streams**.**

Science Needs to Support Implementation: As demonstrated by the ORSANCO compilation of temperature criteria (2005), there is a considerable body of research information on temperature effects on fisheries, and available information might support adoption of protective temperature criteria; however, information is more limited on growth/reproduction than lethality. Maryland's examples show the types of analysis and modeling associated with identifying those coldwater stream areas that are most amenable to conservation and restoration actions. Any action strategies will require site-specific information (e.g. species, benthic community, channel conditions, groundwater inputs). The highest priority is needed on building knowledge of where and why water temperatures are rising in the Chesapeake Bay watershed, and effects on fishery uses, through cost-effective monitoring strategies.

2.4 Scientific, Assessment and Monitoring Needs and Recommendations

<u>Overarching Research, Monitoring, and Modeling Needs</u>

There were specific science needs related to the recommendations in the previous section. The science recommendations to address these needs are grouped under three topics: research, monitoring and modeling. Each topic has an overarching recommendation, rationale, and proposed actions for the CBP partners to consider to address the recommendation. The topics are interrelated and a coordinated and intensive effort will be needed by the CBP partners to carry out the actions needed to address the recommendations.

Research

Recommendation 6: *The CBP partners should enhance and facilitate partnership efforts to collect data and develop tools needed to fill critical knowledge gaps, improve understanding of the impacts of rising temperatures on aquatic ecosystems, and inform management decisions.*

Rationale: The workshop participants agreed that there are critical knowledge gaps and science needs limiting our understanding of the ecological impacts of rising water temperatures, linkages between causes and effects, interactions with other stressors, and how best to mitigate detrimental impacts. Coldwater and coolwater fisheries are at high risk for habitat degradation and loss given their specific temperature thresholds; however, groundwater inputs were recognized as an important component that can mitigate temperature increases and provide thermal refugia. Information on coldwater species other than brook trout is quite limited. Given the many variables affecting the location and impact of groundwater inputs to streams (Snyder et al. 2015; Johnson et al. 2017; Briggs et al. 2018), additional research is needed to assist the CBP partners and relevant stakeholders in identifying streams with groundwater inputs and providing the data necessary to improve existing models and develop new models (see Modeling recommendations). While not as vulnerable as coldwater fisheries to rising temperatures, warmwater fish species are more widespread throughout the watershed, and there is little information on both the direct and indirect effects higher temperatures are having on these species.

Proposed actions to address the research recommendation:

1. Conduct climate vulnerability assessments to better understand both the exposure and sensitivity of species/habitats to rising temperatures, including indirect effects (e.g., invasive species), to better understand overall vulnerability. The assessments would consider various forecasts of land use, climate and hydrogeology in estimating exposure. The results would be useful in understanding the implications of restoration and protection plans and in targeting of resources. Federal agencies could concentrate on regional assessments, while state agencies, local governments, non-governmental organizations, universities and utilities could conduct more local assessments.

2. Collect additional data on the extent of deep and shallow groundwater to improve temperature-based estimates of climate refugia locations at finer spatial scales.

3. Determine how interactions between climate change and land use will affect brook trout and mussel populations including cumulative impacts.

4. Identify genetic metrics necessary to determine brook trout and mussel population resiliency to rising temperatures including adaptive variation to higher temperatures.

5. Conduct targeted research in smaller watersheds to improve understanding of temperature impacts of land use and water management practice; also research the efficacy of BMPs to mitigate temperature-related impacts in line with the science needs as outlined in the Best Management Practices section above.

6. Use an integrative approach combining information on flows, stream power, connectivity, and adaptive capacity to provide a more comprehensive approach for identifying climate refugia.

Monitoring and Analysis

Recommendation 7: *The CBP partners should increase monitoring of water temperature in smaller streams and further analyze existing data from larger streams and rivers to improve understanding of the effectiveness of restoration and conservation of stream communities and fisheries in the face of land-use and climate change.*

Rationale: Information on current temperature monitoring was described in Synthesis Element Paper 10 (Appendix M). A wide array of monitoring needs were identified during the workshop and in the previous section. Collectively they address several topics as described below.

One is stream temperature monitoring to assess if water temperatures are being sustained or ecological thresholds exceeded for sensitive populations of fish and stream communities. High-frequency (sub-daily) monitoring is needed to understand which places are most exposed and sensitive to pulsed heating events such as heatwaves. Additional monitoring is also needed to support state water quality temperature standards.

Documenting effects of different stressors on local stream temperatures is another key topic. Higher-frequency or continuous water temperature monitoring is needed to better understand the relative local influence of various drivers as well as water temperature trends (including seasonal effects). Additionally, a need was identified for monitoring to quantify the relationship between rising temperatures and other water quality constituents, including bacteria in urban areas.

A third topic is to improve and increase monitoring data to better target locations for restoration and conservation activities in the three primary landscapes (coldwater, rural and urban). Monitoring data are insufficient for assessing temperatures in streams draining all landscape areas. Smaller streams generally lack consistent monitoring for temperature and new temperature monitoring is needed in smaller streams important for coldwater fisheries. Additional monitoring is also needed at the air/water interface to identify hotspots where drivers are having a particularly large impact on water temperature to target management.

Finally, there is a need to assess the effects of selected management actions on stream temperature. The effects of selected BMPS on stream temperature is lacking and monitoring is needed to document these changes.

Proposed actions to address the monitoring and analysis recommendation:

1. Use monitoring data to assess changes and factors affecting stream temperatures. Status, trends, and correlations with land use types and changes in air temperature should be investigated. For example, the USGS could consider updating its analyses of changes in stream and air temperature (published by Rice and Jastram, 2015) with newer and more expansive temperature data from the watershed.

2. Evaluate monitoring approaches that have been previously used to assess important ecological thresholds and temperature criteria to protect fisheries. New approaches for temperature monitoring are needed to address watershed-wide effects of climate and land change. The existing data should also be explored for considering updated temperature standards for coldwater (and possibly cool- and warmwater) fisheries by the jurisdictions, similar to the effort by the Maryland Department of the Environment. The data collected by the jurisdictions could be supplemented by an inventory of temperature data compiled by the USGS. The USGS and the jurisdictions could collaborate to examine if multiple types of stream temperature data could be used to identify important ecological thresholds and be considered for improving water quality criteria to protect fisheries.

3. Establish a monitoring network of nested watershed (large to smaller streams) and landscape settings important for biological communities and coldwater fisheries. The CBP Scientific, Technical, Assessment, and Reporting (STAR) team could work with the Climate Resiliency Workgroup (CRWG) to design and implement a monitoring network to assess factors affecting stream temperatures in three landscape areas: coldwater, rural, and urban. One opportunity would be to expand the USEPA Regional Monitoring Networks to detect changing baselines in freshwater wadable streams. The new USGS monitoring effort in the Delaware River Basin should be examined as an approach for Chesapeake Bay watershed monitoring and potential collaboration.

4. Use monitoring and landscape information to help target locations for restoration and protection of areas from rising stream temperatures. Information from the healthy watersheds assessment could be coupled with remote sensing to detect groundwater discharge areas important for sustaining coldwater streams. Partners could include the Healthy Watersheds GIT, USGS, and NASA.

5. Understand temperature and biological response to BMPs in the three habitat settings of the watershed: coldwater, rural and urban. Where possible, take advantage of on-going studies of BMP effectiveness to assess changes to stream temperature. This expanded analysis could be done by academic institutions and other partners conducting small watershed studies.

Watershed Modeling

Recommendation 8: *The CBP partnership should develop new modeling tools and expand the use of CAST and the Chesapeake Healthy Watershed Assessment to better inform the management of watershed fisheries and ecosystems.*

Rationale: Current modeling tools used by the CBP partnership are not sufficient to meet the needs of freshwater fisheries managers. The most widely used CBP tools such as Chesapeake Analysis and Scenario Tool (CAST) and the Chesapeake Healthy Watershed Assessment (CHWA) are built to inform managers on nutrients and sediment, and general watershed health, respectively, at the large scale. They do not provide the types of information nor are they at an appropriate scale needed by fisheries managers making habitat protection and stocking decisions. New tools at the fine scale should be developed in selected areas for local management. New functionality should be added to existing tools to indicate how larger-scale land use and land management decisions would affect habitat.

Proposed actions to address the watershed modeling recommendation:

1. Develop fine-scale, process-based local models in selected areas that better simulate the influence of land use and groundwater on local steam temperatures. The model results would be useful to fishery managers in identifying areas that are in danger of exceeding temperature thresholds important for coldwater species. Improved groundwater simulation will be crucial. Similar efforts by USGS in the Delaware River Basin have developed promising new methods. USGS and other CBP partners may be able to identify resources to pursue development of fine-scale models.

2. The Healthy Watersheds GIT should better integrate the Chesapeake Healthy Watersheds Assessment with regional management models and with local habitat models. Local models may benefit from vulnerability indicators in the CHWA such as projected future development, wildfire risk, and climate change metrics. Findings from local habitat models can be used to improve the understanding of the linkage between vulnerability and habitat indicators in the CHWA. Regional models can share common data sets with the CHWA and can provide it with predictions such as stream temperature effects of climate change. The CHWA should be expanded to include stream temperature as a metric.

3. The Chesapeake Bay Program Office's CAST team should develop scenario outputs related to temperature, fisheries, and biota to inform managers on the aggregate effects of their land use and land management decisions related to the Chesapeake TMDL. This will require the USGS and academic partners to adapt habitat models to be responsive to inputs or outputs available in CAST.

3. TIDAL RISING WATER TEMPERATURES
3.1 What We Know Now: Tidal Storyline

Over the past three decades, the tidal water temperatures in the Chesapeake Bay have been increasing (Figure 7). These changes in tidal water temperatures are primarily driven by global atmospheric forcings (e.g., increasing surface air temperatures) and the warming ocean boundary (Hinson et al. 2021). Water temperature is a key factor influencing basic biological and ecological functions including the distribution and abundance of fishery resources, such as striped bass (*Morone saxatilis*), blue crab (*Callinectes sapidus*), and the eastern oyster (*Crassostrea virginica*) and their habitats, including marshes, submerged aquatic vegetation (SAV) beds, and oyster reefs.

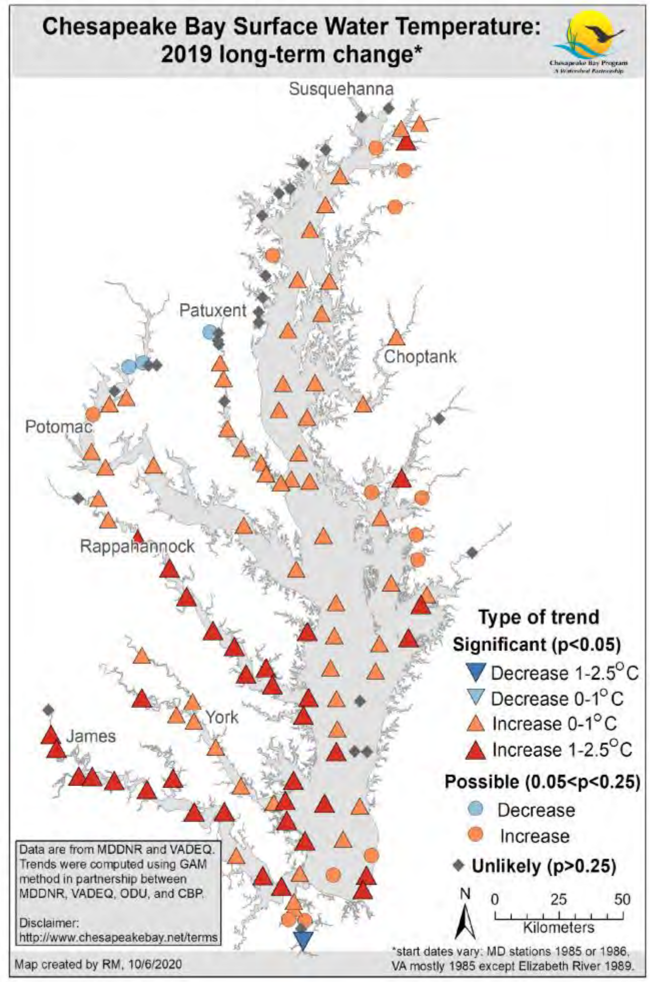


Figure 7: Long term trends in surface water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations from a start date of 1985 or 1986 to an end date of 2019. Source: Chesapeake Bay Program Integrated Trends Analysis Team.

Rising water temperature in the Chesapeake Bay is already having an impact on many species and contributing to ecosystem regime shifts. Some examples of these shifts are declining eelgrass (*Zostera marina*) throughout the polyhaline southern region of the Bay, sub optimal summer temperatures for striped bass, fewer summer flounder (*Paralichthys dentatus*) and increases in species such as red drum (*Sciaenops ocellatus*) and white shrimp (*Litopenaeus setiferus*).

These regime shifts are a result of multiple system drivers (e.g., physical, chemical, biological, and anthropogenic factors) causing significant and persistent changes in the structure, function, and services of the ecosystem (National Marine Fisheries Service, 2022). There is an increased urgency for the scientific and management community to respond to these shifts by providing the information and tools to evaluate the risks and tradeoffs and to develop policies and frameworks to manage adaptively. Having the right monitoring and tidal water temperature change analyses in place to collect and organize data in response to management needs will be critical to inform improved decision-making under changing climate conditions.

Drivers Behind Warming Tidal Waters

Average annual tidal water temperatures in the Bay are estimated to increase by 1° C from 1995 to 2025 as a result of climate change (Shenk et al., 2021; Synthesis Element Paper 6, Appendix J). During this century, Bay waters are predicted to warm by 2 to 6° C, mirroring similar ocean surface water temperatures and global air temperatures, which are predicted to increase by 1.1 to 6.4° C and 3 to 4° C, respectively (Levitus et al. 2001; Meehl et al. 2007; Intergovernmental Panel on Climate Change [IPCC] 2014, 2021; Synthesis Element 3 Paper, Appendix G). Hinson et al. (2021) carried out a comprehensive evaluation of the extent and causes of water temperature change in the Chesapeake Bay over a 30-year timeframe (late 1980s-late 2010s). Major findings from Hinson et al. (2021) are summarized below.

In order of greatest influence, atmospheric forcings, the warming ocean boundary, sea level rise, and increasing river temperatures were identified as four principal mechanisms driving changes in the observed tidal water temperatures in Chesapeake Bay (Figure 8). Atmospheric forcings of increasing surface air temperatures and downwelling longwave radiation were determined to be the main drivers of rising water temperatures throughout the Bay's surface and bottom waters. For instance, atmospheric warming contributed to about 78% of the total change in bottom Chesapeake Bay water temperatures observed from May through October during the 30-year timeframe combined, equal to about a 0.6°C change (Figure 9) (Hinson et al. 2021; Synthesis Element 5 Paper, Appendix I). The role of atmospheric warming on the water temperatures in the Chesapeake Bay is also supported by the trends of increasing air and corresponding surface water temperatures across ~ 92% of the Chesapeake Bay based on more than 30 years of data (1980-2015) reported by Ding and Elmore (2015).

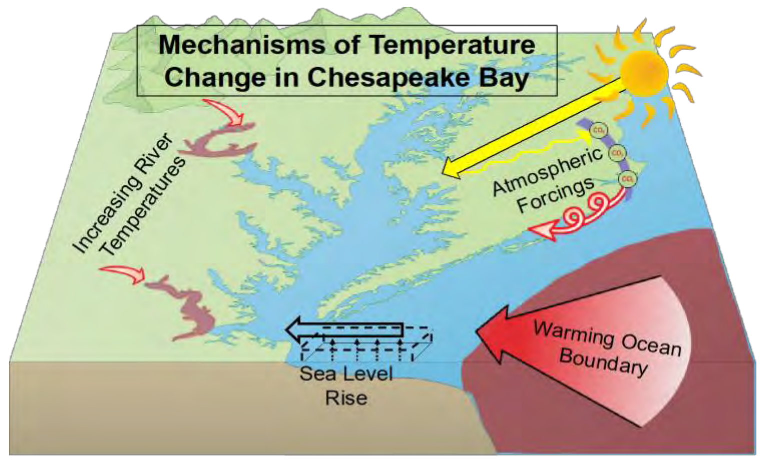


Figure 8: Illustration of the four major mechanisms driving changes in water temperature throughout the Chesapeake Bay's mainstem, tidal tributaries and embayments.
Source: Hinson et al. 2021

The warming of the adjacent Atlantic Ocean was identified as a secondary major driver that contributes to increasing Bay water temperatures, with about a 26% contribution to the overall changes in combined bottom water temperatures from May through October (Figure 9) during the 30-yr timeframe. Regional and seasonal differences were observed with the warming ocean boundary where water temperature increases occurred at the southern part of the Bay near the mouth the most, accounting for more than half of the combined summer warming (June-October) over the 30-yr timeframe. For the remaining months, the warming ocean boundary had a small overall effect on water temperatures (Hinson et al. 2021).

Overall, sea level rise was estimated to slightly cool Bay temperatures across the tidal waters, resulting in a 6% cooling contribution to the overall Bay bottom temperatures over the 30-yr timeframe, about 0.1°C difference (Figure 9) (Hinson et al. 2021; Synthesis Element 5 Paper, Appendix I). Seasonal differences related to sea level rise included an estimated overall cooling in the Bay's mainstem from April through September and slight warming in the winter months (November through February).

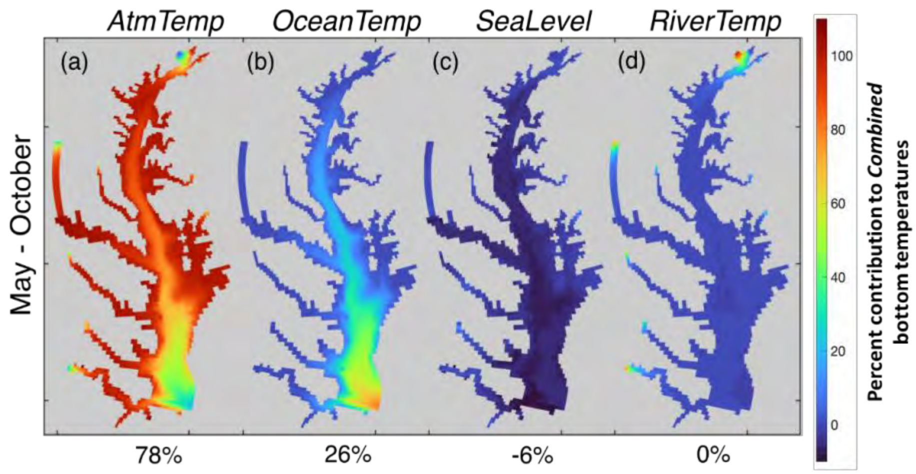


Figure 9: Percent contribution to the total change in main stem bottom temperatures from each sensitivity experiment for (a) atmospheric temperature, (b) ocean temperature, (c) sea level, and (d) river temperature May through October based on a 30-year timeframe (late 1980s-late 2010s). Average main stem percent contributions to total temperature change are denoted beneath each panel. Source: Hinson et al. 2021.

Both surface and bottom waters of the Bay and tidal tributaries exhibited similar temperature changes over the 30-year timeframe (Hinson et al. 2021). Some regional differences in temperature changes were reported, with higher temperature changes estimated for the Susquehanna Flats and adjoining upper Bay mainstem, the lower Bay and mouth of the Bay, and the tidal fresh reaches of the major tidal tributaries. The influence of increasing river temperatures on the warming of tidal waters has a small role in the upper tidal fresh reach of the major tidal tributaries (e.g., Susquehanna, Potomac, and James) and the upper Chesapeake Bay—Susquehanna Flats and the upper Bay mainstem reach down to about Back River on the western shore (Hinson et al. 2021; Synthesis Element 5 Paper, Appendix I). Ding and Elmore (2015) also found local spatial patterns of more rapid warming of surface water temperatures of western tidal tributaries (i.e., Patapsco, Patuxent, and Potomac) compared to the eastern tributaries and portions of the Bay's mainstem. Catchments influenced by high impervious areas in the watershed (i.e., urban heat centers) are particularly vulnerable to thermal pollution linked to riverine discharge (Boomer et al. 2019).

Ecological Implications of Rising Water Temperatures

To identify the ecological implications of rising water temperatures on tidal resources, the STAC Workshop Steering Committee decided on a two-fold approach: 1) recruit experts to develop synthesis papers that summarizes what is known regarding the effects of rising water temperatures on fisheries (Synthesis Element 2 Paper, Appendix F) and SAV (Synthesis Element 3 Paper, Appendix G) resources; and 2) get workshop participants' input on the influencing factors and sensitivities of these resources to rising water temperatures during Day 1 of the workshop. To support the development of the synthesis papers, the CBP's Climate Resiliency Workgroup held a special meeting on June 21, 2021 to get feedback on initial findings about existing knowledge on the effects of rising water temperatures on habitats and living resources. The agenda and meeting presentations can be found in Appendix A and Appendix G, respectively. To expand on the findings in the synthesis papers and further identify ecological implications of rising water temperatures, Day 1 of the workshop was organized into the following sessions (Day 1 agenda, Appendix B):

- Session 1: Identify key factors to consider to assess management implications related to rising water temperatures and ecological impacts
  - What are the direct and indirect positive and negative effects of rising water temperatures on the fishery or SAV resource?
  - What are key factors to consider for the fishery or SAV resource to inform management action around these effects?

- Session 2: Discuss ecological sensitivities to rising water temperatures and certainty of information
  - What do we know of temperature sensitivities on the fishery or SAV resource? What are the research gaps?
  - What temperature-specific analyses would be most useful for informing management for the resource, including temporal and spatial scales?

For each session, the tidal workshop participants were divided into resource-specific breakout groups: SAV (e.g., freshwater/oligohaline, mesohaline, and polyhaline species), oysters, blue crabs, forage (e.g., bay anchovy, menhaden, benthic organisms), and finfish predators (e.g., striped bass, summer flounder). Major findings from the synthesis papers and Day 1 workshop discussions are described below. Details of the Day 1 workshop participants' input can be found in the tidal briefing paper (Appendix P).

Tidal Fisheries Implications of Rising Water Temperatures

The effects of rising Chesapeake Bay water temperatures on living resources were discussed for five key fisheries species chosen on the basis of their economic, ecological, and cultural importance: blue crab, oysters, summer flounder, striped bass, and forage species (i.e. bay anchovy and menhaden). Climate vulnerability scores and bay-specific research, show a range of positive and negative responses of living resources to temperature and other climate change related factors. Positive impacts are likely for blue crab and some forage species (e.g., bay anchovy and menhaden), as warmer temperatures support higher productivity and increased habitat range as species move northward (Synthesis Element 2 Paper, Appendix F). Negative impacts are predicted for oysters due to their already depressed populations as a result of disease, overfishing, and habitat loss.

While oysters can thrive in higher temperature regimes and may experience an increase in habitat range, they are highly vulnerable to other climatic impacts such as ocean acidification and changes in salinity driven by precipitation. Striped bass and summer flounder may experience both negative and positive impacts at different stages of life (larval to adult) and habitat use (rivers and estuaries to marine). The range of responses and potential for localized impacts (e.g., changes in habitat quality and reproductive success within specific tributaries) lead to higher uncertainty in evaluating striped bass and summer flounder vulnerability.

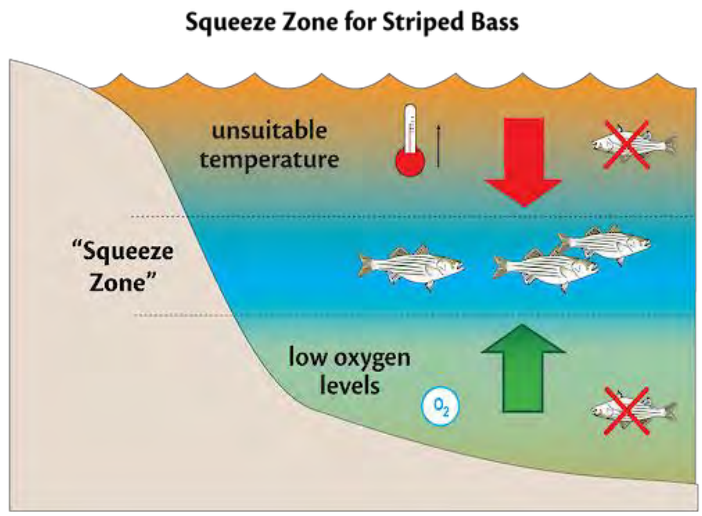


Figure 10: Conceptual diagram illustrating the compressed habitat of the striped bass from the low oxygen levels from the bottom, and the unsuitable temperatures from the surface. Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Boesch 2008.

Workshop participants highlighted how rising water temperatures create a seasonal "habitat squeeze" where striped bass can only thrive in certain regions of the water column, as the higher portions of the water column are too warm, and the lower portions have low dissolved oxygen (DO) levels, compressing suitable habitat to the center (Figure 10) (Boesch, 2008). They also identified the possibility of predator-prey mismatches where rising water temperatures and seasonal shifts could cause unfavorable changes in spring-time spawning of striped bass and availability of food resources (e.g., zooplankton).

Northward shifts in species' ranges are being documented for several species. This is resulting in some Bay species shifting populations north while other species from the south are becoming more prevalent in the Bay. These shifts can result in changes to species abundance and distributions, food web dynamics, fishing behavior and the introduction of new fisheries. Likewise, habitats required by fish and shellfish species are shifting in range and experiencing impacts that lead to changes in fish abundance, distribution and reproduction success.

While rising temperatures are important and do affect species, other climate factors are equally, if not, more important. Existing fishery management approaches will need to adapt by better incorporating climate change impacts into their decision-making for currently managed Bay species as well as additional species that are moving north into the bay and increasing in abundance, such as brown shrimp.

Submerged Aquatic Vegetation Implications of Rising Water Temperatures

There are three primary symptoms of climate change that will directly affect Chesapeake Bay SAV: rising water temperatures, increased carbon dioxide (CO_2) concentrations, and sea level rise (Synthesis Element 3 Paper, Appendix G). Rising water temperatures will likely impact SAV species throughout the Bay in myriad ways, and along with other climate change stressors will complicate restoration efforts. In addition to rising water temperatures, CO_2 concentrations are predicted to increase by 50-160% and sea levels are predicted to rise by 0.7-1.6m.

Temperature impacts to eelgrass (*Zostera marina*) are well understood; warming alone is shown to negatively impact eelgrass, a dominant SAV species in the lower Bay. Chronic high summer temperatures and isolated heat events are associated with mass die offs; the Bay temperatures are already at the upper thermal limits for this cool-water species. Without drastic improvements in water clarity or a reversal of warming trends, viable populations of eelgrass will likely be extirpated from Chesapeake Bay. The Bay's most economically significant fishery–blue crabs (*Callinectus sapidus*)–is directly linked to eelgrass and the habitat it provides.

Temperature's impacts to other Chesapeake Bay SAV species are not as well studied but, based on available data, appear to be less dramatic than those to eelgrass. With that said, current research and preliminary results suggest that increasing temperatures do negatively impact all Chesapeake Bay SAV communities to some extent. The warming Bay temperatures are likely to favor more heat-tolerant species, including widgeon grass (*Ruppia maritima*), certain ecotypes of freshwater SAV, and possibly other subtropical seagrasses. The increasing CO_2 results in a CO_2 fertilization effect that may counterbalance some of the impacts from warming, but unknowns associated with invasive species, pathogens, cyanobacteria, etc. may set that balance awry. Finally, sea level rise affects SAV by increasing the water column depth in which SAV grows, decreasing the light available at SAV leaf blades. Stress from low light conditions can be alleviated by the shoreward migration of SAV in appropriate sediment and nearshore conditions but hardening along much of the Bay's shoreline will prevent that shoreward migration.

Management efforts (i.e., the Chesapeake Bay TMDL) that have reduced nitrogen and phosphorus in the Chesapeake Bay have facilitated recovery of SAV, and SAV are more resilient to all climate stressors (e.g., temperature, CO_2 concentrations, and sea-level rise) if water clarity is maximized. The single most effective action to protect Chesapeake Bay SAV is to sustain and accelerate improvements in water quality and clarity through nitrogen, phosphorus and total suspended solids load reductions. Additionally, SAV restoration efforts for diverse species may mitigate some of the loss of SAV from areas unable to recover without a seed source. The 2020 GIT-funded climate and SAV modeling project will be instrumental in answering many of our questions when complete.

3.2 Management Implications of Rising Water Temperatures

To identify the corresponding management implications of rising water temperatures on fisheries and SAV, Day 1 of the workshop was organized into the following sessions:

- Session 3: Identify management implications
    - Looking at the ecological effects, key factors to consider, and sensitivities related to rising water temperatures identified today. Determining =the management implications for the fishery/SAV resource related to rising water temperatures and when action is likely needed (e.g., within 5 years, 10 years, 20 years, 50 years, etc.).

To identify commonalities and guide discussions on recommendations for Day 2 of the workshop, the identified resource-specific management implications related to rising water temperatures were organized under four main ecological themes: ecosystem-based management, new temperature regime, multiple stressors, and nearshore habitats, further described below.

- Ecosystem-based management strategies aimed to focus on changes in restoration locations and techniques; factoring in rising water temperatures in recruitment estimates, incorporating environmental conditions in fisheries management frameworks; efficacy of current stock surveys; and using nowcast and forecast models for forage species to manage predator stocks accordingly.

- New temperature regime management strategies aimed to focus on changes in spawning success, recruitment, and adult mortalities; monitoring threats from shifting predator distributions and new tropical parasites; and temperature-driven changes on oyster BMP effectiveness.

- Multiple stressors management strategies focused on maximizing improvements in water quality and clarity to build resilience; incorporating habitat squeeze considerations in fisheries management decisions; including shoreline development and other climate stressor effects when assessing SAV recovery; and building in buffers for ecosystem uncertainty in catch quotas.

- Nearshore habitat management strategies focused on co-locating oysters and SAV with one another and/or riparian forest buffers; limiting use of hardened shorelines that negatively affect nearshore resources; and promoting green infrastructure solutions for shoreline protection and habitat.

The management and policy implications of rising water temperatures for the fisheries and SAV resources that were identified by the tidal participants during Day 1 of the workshop are summarized below under the common themes.

1) **Ecosystem-Based Management**: Considerations related to seasonal shifts, prey availability, and habitat change and suitability.

   Management/Policy Implications:

   - <u>SAV</u>:
     - Loss of eelgrass in lower Bay may impact Bay-wide restoration goals; while widgeon grass may fill the niche in most areas, there will be ecological consequences (e.g., timing of emergence of spring habitat for crabs and fish).

   - <u>Oysters</u>:
     - Restoration locations and techniques may need to change to account for rising temperatures and impacts of other stressors.
     - Temperature and seasonal changes may affect growth rates and reproduction which in turn could require adjustments to harvest openings and limits.

- Blue crab:
    - Possible need for new harvest schedules and revised female-specific management to account for temperature change impacts; assess change in efficacy of current winter surveys and stock assessment strategies.
    - Incorporate environmental conditions like temperature and habitat when managing fishery; include monitoring of critical parameters influencing blue crab populations.

- Forage:
    - Support more research to evaluate the forage base and understudied species; aim for standardization of sampling methods and regional definitions for measuring restoration success.
    - Support development of nowcast and forecast models for forage species and establishment of forage indicators and thresholds for suitable habitats – manage predator stocks accordingly.
    - Minimize marsh and SAV habitat loss for forage populations in conservation strategies.
    - Consider changes in forage composition and abundance due to warming temps.

- Striped bass:
    - Collect more long-term fish and prey data to model carrying capacity of Chesapeake Bay in relation to temperature and DO conditions to improve model.
    - Factor in rising water temperatures in recruitment estimates under current management formula.
    - Quantify effects of ecosystem-based factors (e.g., change in food web structures and habitat availability) on striped bass populations and build into management strategies.
    - Incorporate considerations of seasonal change effects on spawning and migration timing/duration (possible predator-prey mismatch scenarios may occur).

2) **New Temperature Regime**: Considerations of the pros and cons of an ecosystem shift to a new temperature regime in Chesapeake Bay (e.g., changes in species distributions; new species moving in; new pathogens; BMP effectiveness).

Management/Policy Implications:

- SAV: Whether to focus on species or genotypes that can thrive in future conditions (e.g., widgeon grass, heat-adapted eelgrass, or new sub-tropical species) that also provide ecosystem benefits.

- Oysters: Consideration of temp-driven changes on effectiveness of oyster BMPs to remove nutrients.

- Blue crab: Increase monitoring for threats from shifting predator distributions and tropical parasites.

- Forage: Consider potential competition for resources from invasives and new species moving into the Chesapeake Bay.

- Striped bass: Consider changes in spawning success, recruitment and adult mortalities associated with temperature changes.

3) **Multiple Stressors**: Considerations related to co-occurring stressors (high temperatures, low dissolved oxygen, salinity fluctuations, increased disease prevalence, etc.) and extreme events (e.g., marine heat waves, increased precipitation).

   Management/Policy Implications:

   - SAV:
     - Maximizing water clarity is key; SAV substantially more resilient to temperature stress in clear water; sustaining and accelerating improvements in water quality and clarity through N, P, and TSS load reductions and appropriate BMP implementation will be vital
     - Shoreline development and other climate stressors (e.g., sea level rise) will affect SAV recovery – shoreline hardening negatively affects nearshore SAV and limits shoreward migration

   - Oysters:
     - Fishery: may need more monitoring/management of diseases
     - Aquaculture: more labor may be required due to increased fouling on cages, faster oyster growth rates, and longer growing season; increased movement of oysters away from areas with poor water quality

   - Forage:
     - Continue to support water quality improvements as soft bottom mud is the predominant habitat for many benthic forage species

   - Striped bass:
     - Consider habitat "squeeze"/compression (low bottom DO and warm surface water temperatures) when making management decisions (e.g., recreational fishing)
     - Build in buffers for ecosystem uncertainty in catch quotas – rising temperatures and increases in other stressors could exacerbate already high mortality rates for striped bass

4) **Nearshore Habitats**: Considerations related to strategically co-locating certain restoration efforts or watershed BMPs to maximize resilience of nearshore habitats.

Management/Policy Implications:

- Oysters and SAV:
  - Consider co-locating oysters/freshwater mussels with SAV, and/or riparian forest buffers.
  - Strategic siting for shoreline and flood protection.

- Striped bass:
  - Consider land-based BMPs, conservation measures and nearshore restoration to increase resilience of key spawning areas (e.g., Susquehanna Flats, Choptank River, and Potomac River).

- SAV and Forage:
  - Limit use of hardened shorelines which negatively affect nearshore resources and promote green infrastructure solutions that provide shoreline protection and habitat.

3.3 Management Recommendations

The objectives for Day 2 of the workshop were to: 1) identify management and policy recommendations, and 2) identify the research, monitoring, or analysis needs to support these recommendations (Day 2 agenda, Appendix B). The management implications for the fisheries and SAV resources that were identified during Day 1 of the workshop were used to inform the Day 2 discussions based on four main themes: ecosystem-based management, new temperature regime, multiple stressors, nearshore habitats. Day 2 of the workshop aimed to answer two main questions: 1) how could current management or policy actions be adapted to address rising water temperatures, and are there entirely new management options that should be considered and 2) what additional science and/or information would you need to implement the management recommendations?

The tidal participants were randomly divided amongst three breakout groups during four sessions based on one of the four main themes to discuss management recommendations and corresponding science needs. The goal was to develop 1-2 management recommendations per group per session and identify science needs for those recommendations. At the end of the sessions, the tidal session workshop leadership convened to consolidate the recommendations, so that similar recommendations were combined to create one synthesized recommendation and to sort out those recommendations that were not as developed. The tidal session workshop leadership presented the final list of recommendations to the tidal project team subgroup, where recommendations were reviewed and assessed for feasibility to implement within the next 3 years and their impact on mitigation and/or resilience. The breakout group's individual management recommendations for each theme, the consolidated recommendations, and the feasibility and impact input can be found in Appendix R.

Post-workshop, the tidal session workshop leadership team selected five recommendations that generated the most interest from the tidal participants based on their feasibility and impact and were the most developed during the workshop sessions. While Day 2 of the workshop had separate sessions for the ecosystem-based management and the new temperature regime themes, the recommendations for these two themes were grouped together since the ecosystem-based management discussions carried over into the new temperature regime session resulting in the overlap of ideas. As a result, recommendations 1, 2, and 3 address both these themes. Recommendation 4 emerged from the Multiple Stressors session and recommendation 5 emerged from the Nearshore Habitats session. The five management recommendations and the themes that guided their development are described below.

Ecosystem-Based Management and New Temperature Regime Recommendations

Recommendation 1*: Establish Chesapeake Bay-wide striped bass fishing guidance based on temperature and dissolved oxygen thresholds to reduce catch and release mortality. Consider developing habitat condition thresholds and fishing guidance for other recreationally targeted species at risk during periods of poor habitat conditions.*

Rationale: Warm surface waters and low dissolved oxygen bottom waters outside the optimal ranges for fish survival minimizes usable habitat, commonly referred to as a “habitat squeeze.” Fish experiencing this habitat squeeze are under stress and are more susceptible to mortality associated with catch and release recreational fishing. This stress can be minimized by notifying anglers of days when habitat conditions are poor and discourage fishing that could result in catch and release mortality.

Implementation Actions:

1. Host focused meetings with the joint Sustainable Fisheries and Habitat GITs, and the Fish Habitat Action Team (FHAT), to review existing science on temperature and oxygen thresholds, application of the science to develop bay-wide thresholds and guidance. The desired outcome of these meetings is to establish temperature and oxygen thresholds for striped bass and other key species based on best available science (e.g., number of days above a certain temperature in combination with hypoxic conditions to inform guidance sent to anglers and possibly other fishing restrictions).

2. Convene discussions at the Sustainable Fisheries GIT (SFGIT) with managers and invited anglers to a) consider the temperature and oxygen thresholds findings of the FHAT and develop and communicate guidance to anglers on the environmental thresholds and ways to modify fishing practices to reduce mortality when fish are most vulnerable, b) consider fishing restrictions in areas where conditions exceed thresholds to reduce fishing mortality, and c) develop options for how the thresholds could be built into fishery management plans at state and regional (Atlantic States Marine Fisheries Commission) levels.

There are current examples that apply threshold concepts and could be expanded Bay-wide. For instance, the Maryland Department of Natural Resources' Click Before You Cast simple yet informative approach to describing conditions for fishing could be merged with a temperature advisory system similar to Maryland DNR's system for anglers fishing striped bass. Maryland DNR's advisory system uses a stoplight approach based on temperature thresholds to inform fishing behaviors that minimize stress to striped bass (green = fishing conditions are normal; yellow = forecasted temperatures indicate extreme care encouraged – keep caught fish for later release in water; red = forecasted temperatures indicate not to fish for that species after a certain time in the morning or fish other less vulnerable species) (MD DNR, 1). Similar applications could be put in place for Virginia and Potomac tidal fishery programs. Additionally, established thresholds could be used to inform fishing decisions, particularly in the summer, when temperatures are high enough that would substantially, negatively affect the fish.

Science Needs to Support Implementation:

1. Synthesize existing science to determine temperature and DO habitat condition thresholds for striped bass and other key species. There may be a need for more information on how air and water temperatures interact and its effect on species-specific mortality risk that requires lab and field studies. However, several studies have been conducted on striped bass and these should serve as the starting point.

2. Conduct investigations to better understand behavior of anglers on the water (i.e., throwing back all fish, keeping some fish). This could include gathering additional information about behavior of the fishers when they are out on the water such as are they just going out to catch and release, do they catch their limit and head back to shore, or do they catch their limit and continue to fish and catch and release.

3. Develop habitat suitability models and indicators for key fishery resources. For example, NOAA and the CBP have funded several projects quantifying the impacts of temperature and other ecosystem drivers on forage (Fabrizio et al. 2020, Woodland et al. 2022), striped bass (Dixon et al. 2022) and summer flounder (Fabrizio et al. 2022, Schonfeld et al. 2022).

Recommendation 2*: Develop and implement a strategy to improve communications between living resource managers, scientists and stakeholders on the new temperature regime, the impacts and management response/adaptation strategies.*

Rationale: It is clear the Chesapeake Bay is undergoing an ecosystem regime shift driven by climate change and other factors. New species and new fisheries are emerging in the Bay, and existing species and fisheries are undergoing change. Some species and fisheries will be lost from the Bay entirely. There is a need to better communicate the impacts of rising water temperatures to manage the public's expectations of what the Bay will look like.

Implementation Actions:

1. Sustainable Fisheries and Habitat GIT representatives meet with the CBP communications team to scope out a communications strategy conveying that the shift to a new temperature regime in the Bay is already underway. Change has already occurred in the Bay's ecosystem, potentially bringing new species and fisheries, as well as impacting current species and fisheries. This strategy should be tailored to focus on various audiences–policy-makers, managers, and residents, as each stakeholder group has their own unique perspectives with regard to this changing system.

Science Needs to Support Implementation:

1. Understand where the gaps are in our current communication strategies
    a. Research communication strategies to target specific audiences

2. Social science research to help understand decision making (e.g., understanding behavior of anglers on the water when throwing back or keeping catches, understanding property owners' choice in SAV and shoreline protection)

3. Development of communication strategies for specific audiences (e.g., policy-makers, managers, residents, local partners)
    a. Examples: communication regarding shoreline protection decision-making, public health concerns regarding marine heat waves and state of the fisheries, the effect that the loss of eelgrass will potentially have on the blue-crab industry.

Recommendation 3***:*** *Hold a workshop with multiple fishery stakeholders to explore strategic, long-term ways to advance ecosystem approaches to fishery management in the Bay that incorporate climate change. These approaches would need to address current fisheries management practices that need to be reassessed based on current climate modeling, as well as developing new fisheries management practices that will address the new, potential fisheries that will develop as southern species move into the Bay. To better inform decision-makers, there is a need to develop climate scenarios and assess the risks of environmental drivers on fishery species and their habitats to inform fishery management planning and decisions.*

Rationale*:* Increasing air and water temperatures along with other climate change drivers are already leading to changes in the abundance and distribution of coastal and Chesapeake Bay fisheries as well as their habitat. At the same time, southern species are moving northward and showing up in greater abundances in the Chesapeake Bay and in some cases creating new fishery opportunities. The current fishery management framework is not considering these changes in a strategic, systematic, coordinated way.

Implementation Actions:

1. Hold a focused Sustainable Fisheries GIT forum to identify the changes that are occurring and develop scenarios for how the Bay and fisheries will change over the next 20 years.

2. Convene fishery survey experts to discuss if changes are needed on how we conduct fish stock surveys under changing climate conditions. Examples are:
    a. Blue crab winter dredge survey catchability estimates.
    b. Stock assessment surveys to better capture shifts in temperature ranges/seasons and response to emerging fisheries.

Science Needs to Support Implementation:

1. Improve environmental monitoring of surface and bottom temperature, dissolved oxygen and fish habitat condition. Pair fishery survey data and telemetry fish tag detections with data on changing environmental conditions to better understand impacts on fishery resources at temporal and spatial scales that can be used by managers.

2. Explore a state of ecosystem report level synthesis for the Chesapeake Bay to track how climate change is progressing and for use by managers to adapt actions addressing the changes appropriately. Determine the appropriate time frame for this report on an annual, 3-year, 5-year, or other basis.

3. Better understanding of physiological response of certain species (e.g., lower trophic organisms; need *in situ* monitoring to better assess change).

4. Explore assessments for emerging fisheries to facilitate management as climate change creates conditions for these fisheries to be economically viable.

5. Consider establishing monitoring stations where there are significant fisheries habitat and spawning grounds (long-term monitoring currently is more set up to characterize large bay segments). There are certain sentinel sites with continuous monitoring sites that could be considered (e.g., the National Estuarine Research Reserve System).

6. Evaluate need for zooplankton monitoring at spawning and nursery areas.
    a. The Chesapeake Bay is changing. While it is expected that improvements in habitat due to nutrient reductions and reduced fishing mortality rates will drive improvement in the Bay's living resources and fisheries, past monitoring (1984-2002 and 2011) indicated major negative shifts in phytoplankton, zooplankton, fish, and shellfish inconsistent with expectations from the Bay cleanup. Zooplankton are an important link in the food chain that transform nutrients to fish production by feeding fish larvae of many species and providing forage for forage fish. Zooplankton monitoring can be useful for understanding ecosystem changes associated with large-scale efforts to improve water quality in Chesapeake Bay and is currently a missing building block of the framework for ecosystem-based fisheries management in the Bay.

7. Improve information on drivers of natural mortality and recruitment success for key fishery species and build those drivers into ecosystem models. These improved models will then provide better information on how climate change will affect fisheries. Conduct research on and enhance the existing ecosystem models to better capture climate change drivers and impacts.

8. Better understanding of how the loss of late-winter/spring eelgrass habitat in the polyhaline region of the Bay has and will continue to impact the blue-crab fishery.

Multiple Stressors Recommendation

Recommendation 4*: An interdisciplinary team of scientists, resource managers, meteorologists, and communicators should collaborate to design and create a publicly available marine heat wave alert system and explore options to incorporate information on multiple stressors (e.g., low dissolved oxygen). The system would define estuarine marine heat wave conditions and send push notifications to stakeholders about safety and how to mitigate impacts on human health and living resources.*

Rationale: Marine heatwaves are defined as a short period of anomalous higher ocean temperatures and can be caused by ocean currents, air-sea heat flux, and warming through the ocean surface. Marine heat waves in the Chesapeake Bay are increasing in frequency, number of days per year and yearly cumulative intensity (Mazzini and Pianca, 2022). If trends persist, by 2100 the Chesapeake Bay will reach a semi-permanent marine heat wave state. Marine heat waves directly and indirectly negatively impact habitat, living resources, and human communities. Marine heat waves are associated with harmful algal blooms, increase in bacteria such as vibrio, mortality of SAV and other organisms, further decreases in bottom dissolved oxygen, shifts in species composition, increased risk during recreational activities and impacts to fishing and aquaculture. During a marine heat wave, it is important to change how/when/where fishing and aquatic recreation are occurring to minimize impact on both people and aquatic life.

Implementation Actions:

1. The Scientific and Technical Advisory Committee (STAC) and/or Scientific, Technical, Assessment and Reporting (STAR) team convene CBP partners and other relevant experts such as NOAA's weather service and Climate Program Office to review the state of the science and scope out a conceptual design for a heatwave alert system. During this workshop, participants will consider the degree of focus on human health and/or living resource risk, the scale (e.g. jurisdictional, Bay-wide, or tributary specific), alerts based on real-time monitoring data (retrospective) vs. forecast models (prospective), and which agency would issue alerts (e.g., MD DNR/VADEQ, NWS, etc.).

2. Review the following topics and issues in planning for the recommended workshop/meeting.
   a. Incorporate human health risks associated with marine heat waves and guidance on mitigating impacts.
   b. Design and develop a mobile application or incorporate into an existing application (such as Eyes on the Bay), including the impact and what the public should do to limit their impact (i.e., don't take fish out of the water).
   c. Test to ensure user-interface is easy and straightforward for end-users.
   d. Partner with the meteorological community and the media to incorporate into weather forecasts and warnings as a real time push notification.

e. Examples of similar existing alert systems include:
    i. NCCOS developed a Gulf of Mexico Harmful Algal Bloom (HAB) Forecast system for Texas and Florida; end-users can sign up for HAB alerts through this tool, which can help inform any behavior when interacting with the Gulf.
    ii. NCCOS developed a Chesapeake Bay *Vibrio vulnificus* Forecast system with modeling for the previous six days, current day, and the next day. End-users can opt to receive forecast updates and breaking news on *Vibrio*.

3. If experts and stakeholders agree that such a product would be valuable to reducing risk to people and living resources and have developed a conceptual design, then consider GIT funding for product development.

Science Needs to Support Implementation:

1. Review current definitions of marine heat waves (e.g. Hobday et al. 2016, Mazzini and Pianca, 2022) and conduct research to determine an appropriate definition for Chesapeake Bay (or tributaries as appropriate).

2. Explore real time monitoring of marine heat waves and need for forecast products.

3. Consider a marine heat wave indicator that connects with living resource management and guidance to the public.
    a. Link marine heat waves to living resources by analyzing marine heat waves and fishery survey data such as ChesMMAP.
    b. Incorporate dissolved oxygen and links to habitat preferences of key species such as striped bass, blue crabs, oyster, and SAV.
    c. Synthesis Element 9 Paper (Appendix L) provides conceptual ideas and potential existing data sources that could inform a fisheries marine heat wave indicator.

4. Development of the warning system.

5. Outreach to the public and to partners during development to incorporate stakeholder needs.

Nearshore Habitat Recommendation

Recommendation 5: *Chesapeake Bay Program partners should develop common criteria and metrics to help target, site, design and implement tidal natural infrastructure projects in the nearshore where ecological and climate resilience benefits are highest. A priority should be placed on the use of natural infrastructure by conserving natural shorelines including marshes, wetlands, oyster reefs, and SAV and creating living shorelines in areas that incorporate multiple habitat types. Following targeting and prioritization of projects, emphasis should be placed on* *accelerating preferred designs, providing information on funding opportunities and providing technical drafting assistance for implementation proposals.*

Rationale: Shoreline hardening along the coastlines of the Bay continues despite regulations in Maryland and Virginia to promote natural infrastructure, including living shorelines, tidal wetlands, and other nearshore nature-based feature, where feasible and beneficial (e.g. The Living Shoreline Protection Act in Maryland and Virginia's Living Shoreline Requirement in SB776). Hardened shorelines adversely impact organisms and ecosystems including fish habitat, SAV, water fowl, and water quality. Natural infrastructure provides ecosystem services in the face of a changing climate, including shoreline erosion protection, refuge for many fish and shellfish species from multiple stressors, protection from rising water temperatures, sedimentation mitigation, and improved water quality. Natural infrastructure is an opportunity to create a link between protecting communities from flooding hazards while also enhancing habitat to benefit living resources and recreational activities. Evidence shows natural infrastructure provides multiple climate, ecological and social benefits (Sutton-Grier et al. 2015) and is a shoreline protection option that provides longer term resilience when compared to the hardened options (Currin 2019) NOAA defines "natural infrastructure" as healthy ecosystems–e.g., forests, wetlands, floodplains, dune systems, submerged aquatic vegetation, and reefs). These benefits and ecosystem services include storm protection through wave attenuation or flood storage capacity, enhanced water services and security, increased habitat for vertebrate and invertebrate species, improved water quality, and protection from shoreline erosion. While many terms exist for this infrastructure (e.g., living shorelines, nature-based infrastructure, green infrastructure, and natural/nature-based features), for the purpose of this report, natural infrastructure covers all these terms.

Implementation Actions:

1. Develop siting criteria and targeting tools to facilitate development of more project designs and project implementation proposals.
    a. Convene a meeting through Scientific, Technical Assessment and Reporting (STAR) team that includes key CBP experts and stakeholders working on nearshore restoration (wetlands, living shorelines, oysters, SAV) to compile existing criteria and targeting tools and look for ways to integrate information into the GIS team's Cross GIT mapping platform. Two current GIT funded projects will aid in targeting potential natural infrastructure projects and help identify regional partners and funding sources: "Synthesis of Shoreline, Sea Level Rise, and Marsh Migration Data for Wetland Restoration Targeting" and "Partnership-Building and Identification of Collaborative Tidal Marsh Adaptation Projects." A third GIT-funded project assessing the impacts of climate stressors on SAV may also provide siting information for SAV restoration and natural infrastructure solutions.
    b. Use Federal Emergency Management Agency (FEMA) hazard mitigation plans at community level for targeting. The plans are a good information source on hazard information and flood impacts which can be linked to habitat protection goals.

2. Conduct outreach to homeowners. Review current studies on behavioral drivers behind shoreline hardening decisions and summarize findings to develop effective communication strategies for homeowners to increase the use of living shorelines over hardened structures. Work with regional partners (e.g., Riverkeeper) to communicate with residents.
    a. Explore recent efforts such as MD Department of Natural Resources' (DNR) Social Marketing to Improve Shoreline Management Project, Virginia Institute of Marine Science's (VIMS), and the CBP SAV and Communication Workgroup's Social Marketing Project on SAV: Barriers and Benefits with regard to shoreline property owners, and identify gaps in current communication strategies.

3. Develop a Chesapeake Bay specific guide for homeowners, city and town planners, and developers with a menu of living shoreline options, where they work best and how to integrate other habitats (SAV, oysters, etc.).

4. Hold discussion with members of the SAV Workgroup and FHAT to explore development of a funding proposal for a proof of concept project that integrates SAV and oysters.

Science Needs to Support Implementation:

1. Detailed analysis of costs of natural infrastructure versus hardened infrastructure (e.g., bulkhead, rip rap) including long term maintenance costs.

2. Threshold analysis to determine when ecological impacts or benefits occur from natural infrastructure implementation.

3. Development of criteria for targeting where multiple benefits and ecosystem services can be optimized.

4. Use of models to increase understanding of habitat change from sea level rise as to leverage change for different restoration efforts (subtidal oysters versus intertidal).

5. Development of pilot studies co-locating SAV and oysters to increase understanding of the synergistic benefits, such as the buffering capacity of SAV beds to minimize the effects of coastal ocean acidification on nearby vulnerable shelled organisms (e.g., oysters). Coastal ocean acidification refers to increases in carbon dioxide in the water column absorbed from the atmosphere resulting in decreases in pH and carbonate availability. This work would build on the current study by Rivest et al. (VIMS and Old Dominion University) assessing ocean acidification thresholds in Chesapeake Bay.

3.4 Scientific, Assessment and Monitoring Needs and Recommendations

Overarching Research, Monitoring, and Modeling Needs

Throughout this STAC workshop effort, a multitude of management recommendations and associated science needs were identified. Many of these science needs are cross-cutting and relevant to more than one management recommendation above. To make overall progress on addressing rising water temperatures on living resources, a coordinated effort will be needed by CBP partners on cross-cutting science needs. The overarching research, monitoring, and modeling needs are described below:

Research

The CBP partners should focus on reviewing and compiling current research related to social science and understanding the behavior of stakeholders interacting with the Chesapeake Bay, specifically as it pertains to shoreline protection and hardening, fishing activity, and communication about current and future Bay ecosystem status. The CBP should then identify and address gaps in current knowledge about these topics. Additionally, there is a need for research to better understand how and to what degree could watershed BMPs minimize warming for nearshore habitats within tidal tributaries in short to mid-term timeframes related to cooling benefits for SAV and fish.

Monitoring and Analysis

The CBP partners should focus on improvements to long-term monitoring networks surrounding water temperature, hypoxia, salinity, nutrients, and water clarity to help better assess change in habitat conditions for SAV and fisheries. The inclusion of *in situ* fish and plankton monitoring would allow for better assessment of seasonal shifts in temperatures and whether recruitment is affected due to unfavorable changes in spawning timing and prey resources. Furthermore, more habitat monitoring is needed to better understand how SAV community changes from seasonal temperature shifts and the timing differential of eelgrass and widgeon grass will affect habitat-use and productivity of blue crabs and other fisheries.

Modeling

There is a need for current modeling to aid in decision-making as it relates to rising water temperatures in the Chesapeake Bay. The CBP and partners should focus efforts on modeling improvements to help carry out the above identified implementation actions. In general, there is a need for greater habitat suitability modeling that integrates multiple climate stressors on SAV and fisheries, understanding and modeling of the linkages between environmental change and its impacts on living resources, and spatial analyses and modeling to help in nearshore project prioritization. To accomplish these goals, model improvements are needed in simulating shallow water parameters (e.g., dissolved oxygen) at finer scales and incorporating unstructured model grids to fit complicated shorelines. Additionally, forecasting models that project habitat (e.g., SAV, tidal wetlands) migration potential with sea level rise and shorter term changes (1 versus 5-10 years) to support fisheries-related decision-making are of interest to various stakeholders.

4. COMMONALITIES AND LINKAGES BETWEEN WATERSHED AND TIDAL RISING WATER TEMPERATURES

Through presentations and discussions held during the plenary sessions combining participants from the concurrent watershed and tidal sessions, the following common themes and linkages were identified:

- **Modeling tool improvements**: Modeling at a finer scale, incorporating temperature change in our modeling systems, and improving the connections between the models we use and monitoring of living resources, are needed to enable us to better respond to rising water temperatures.

- **Expanded monitoring**: Expanding the existing monitoring networks to place more emphasis on collecting the data necessary to track and better understand water temperature change, and a focus on smaller streams, are necessary enhancement to the partnership's existing watershed and tidal monitoring networks.

- **Paired water and air temperature measurements**: Improving our ability to pair information about trends in water temperature with trends in air temperature at the appropriate scale will greatly improve our understanding of the forces driving the observed watershed and tidal rising water temperatures and support management decisions.

- **Targeting**: Incorporating consideration of water temperatures into targeted implementation of practices and the co-location of practices, including different combinations of habitat restoration and land conservation activities, is absolutely necessary to ensure future implementation efforts account for continued rising water temperatures.

- **Land use planning**: Making sure that planners and other people who make land use decisions are armed with essential information and science about the impacts of their decisions on rising water temperatures is key to mitigating future rises in water temperatures in the watershed and nearshore tidal environments. It is important to consider natural infrastructure strategies to maximize water quality, habitat, and living resources benefits that also build resilience to warming water temperatures and other climate change conditions (e.g., increased precipitation, sea level rise). While gray infrastructure and hardened shorelines are used to minimize climate change impacts related to watershed and coastal flooding and shoreline erosion, they also negatively affect water temperature and natural resources. Supporting research and enhancing knowledge on how best to implement land use strategies that maximize climate resilience, water quality, habitat, and living resources benefits will allow for better overall adaptation to future climate conditions.

- **Thresholds**: Understanding thresholds and communicating about the implications of thresholds to decision-makers and the public would improve understanding of why management tools and actions are needed to respond to rising water temperatures.

- **Nature-based features**: Restoration using natural resources both on the land and in the water is necessary to help with mitigation or to build additional resilience to rising water temperatures. Nature-based practices, such as forest buffers, wetland restoration, living shorelines, and SAV restoration provide multiple ecological and climate resilience benefits in addition to sequestering carbon from the atmosphere. Quantification of these benefits and increased understanding on the spatial and temporal shifts to nature-based features will be important for effective natural resource management under future climate conditions.

- **County comprehensive plans**: Building tighter linkages between the growing scientific understanding of rising water temperatures and updating and implementing county comprehensive plans are essential to future planning to mitigate and adapt to rising water temperatures.

- **Communication**: Communication with each other, communication with decision-makers, and communication with the public is key to ensuring we all start to directly consider the implication of rising water temperatures in our day-to-day management decision making.

5. MANAGEMENT PANEL INSIGHTS

A panel discussion among managers drawn from across the partnership was scheduled near the end of the second workshop held on March 15, 2022. Panel members provided the following series of insights for considering rising water temperatures within the partnership's shared decision-making efforts:

Stay focused: We need to recognize that protecting existing forest, promoting riparian buffers and promoting smart BMPs – that is, staying focused on implementation of the Chesapeake Bay TMDL – will help give the Bay and watershed ecosystems the resilience they need to stay the course in rapidly changing temperature regimes. Recognizing that many partners are feeling overwhelmed by taking on new things, we need to keep focused on incorporating consideration of rising stream temperature into existing Chesapeake Bay Program goals.

Keep positive: We heard a lot about ongoing changes and projected future changes to the watershed and the Bay ecosystem due to rising water temperatures. How do we tell a compelling story which reflects such changes? We are already witnessing changes in our Bay fisheries due, in part, to increasing water temperatures throughout the Bay. We need to be telling those stories, realizing that continued changes are inevitable, and we will need to adapt to those changes through time.

Put More Attention on Smart BMPs: BMPs and natural infrastructure are all really important in this situation. We've been focused on water quality, but if there are water quality BMPs that are further heating waterways, we need to identify alternatives that could be implemented in multiple landscape contexts. Although it is not always possible to eliminate the use of heating BMPs, we can strive to use our continuing technological advances to reduce the heating of runoff from cities, farms and forests.

Increased integration of monitoring: Our monitoring programs need to better integrate considerations of smaller streams, groundwater, living resources and air temperatures in the context of rising water temperatures. We also need new monitoring approaches which will enable us to document the duration and impact of temperature shocks to receiving urban streams.

Communicate better and more often: To successfully cause behavior modification, people need to better understand the relationship between rising temperature and what they can do to correct it. This strategic communication is needed around a variety of topics, including fisheries and property maintenance. Communicating about rising water temperatures provides us with an additional means for communicating why taking these actions are so important.

It's about saving trees, not just replanting new ones: We need to quantify what we are losing when we cut down mature trees and forests and put these values in context with what we gain when we plant seedlings. The cost of losing mature forest needs to be better communicated.

Rethinking water quality standards: We need to challenge ourselves to update our states' water temperature standards and articulate what a state-of-the art standard might look like at the local scale.

Fisheries management will be different with rising water temperatures. Stay focused, keep positive, and recognize Bay fisheries are changing and will continue to change. We will likely have completely new fisheries in the future and lose fisheries which have been associated with Chesapeake Bay for decades over time. We must continue to manage our fisheries keeping in mind the entire life cycle of each fishery population, particularly for this species which spent part of their lives outside of Chesapeake Bay. We really need to make sure, before we approach our vast array of fishery stakeholders with new management approaches, that we are connecting the dots of what is happening inside and outside of the Bay. We need to take full advantage of the climate scenario planning initiative between the Atlantic States Marine Fisheries Commission and the Mid-Atlantic Fishery Management Council.

Use targeting to act smarter, not delay. We have a lot of targeting tools that can help us identify which lands to conserve and where to place the most effective BMP. We could use these tools more effectively to factor in consideration of rising water temperatures when identifying which practices should be implemented where. However, we shouldn't delay implementation of actions we know are needed now in the interest of further improving our existing targeting tools.

There are opportunities at the land-water interface. With new federal funding opportunities, we need to think through how we can best position ourselves in the Chesapeake Bay to better address strategies to maintain the natural systems we have along the shoreline. We need to carry out more restoration and more habitat protection at that near-shore interface to provide refuge to a number of species, such as blue crabs, oysters, and forage species in the face of rising water temperatures.

6. REFERENCES

Boesch, D.F. (editor). 2008. Global Warming and the Free State: Comprehensive Assessment of Climate Change Impacts in Maryland. Report of the Scientific and Technical Working Group of the Maryland Commission on Climate Change. University of Maryland Center for Environmental Science, Cambridge, Maryland. This report is a component of the Plan of Action of the Maryland Commission on Climate Change, submitted to the Governor and General Assembly pursuant to Executive Order 01.10.2007.07.

Boomer, K., Boynton, W., Muller, A., Muller, D., and Sellner K. 2019. Revisiting Coastal Land-Water Interactions: The Triblet Connection. STAC Publication Number 19-005, Edgewater, MD. 37 pp.

Currin, C. 2019. "Living Shorelines for Coastal Resilience." *Coastal Wetlands*, edited Gerardo Perillo, Eric Wolanski, Donald Cahoon, and Charles Hopkinson. Elsevier, 2019, pp. 1023-1053. doi: 10.1016/B978- 0-444-63893-9.00030-7.

Ding, H. and A.J. Elmore, 2015. Spatio-Temporal Patterns in Water Surface Temperature from Landsat Time Series Data in the Chesapeake Bay, U.S.A. Remote Sensing of Environment 168: 335–348. https://doi.org/10.1016/j.rse.2015.07.009.

Dixon, R. L., Fabrizio, M. C., Tuckey, T. D., and Bever, A. J. 2022. Extent of Suitable Habitats for Juvenile Striped Bass: Dynamics and Implications for Recruitment in Chesapeake Bay. Virginia Institute of Marine Science, William & Mary. doi: 10.25773/v87b-6b43.

Goetz, D., Borsuk, F. 2022. *A Conservation Framework for Increasing Resiliency for Maryland's Brook Trout* [PowerPoint slides]. Maryland Department of Natural Resources. https://www.chesapeake.org/stac/wp-content/uploads/2022/10/STAC-MD-Update.Goetz_.03.11.22.pptx.pdf

Fabrizio, M. C., Tuckey, T. D., Bever, A. J., and MacWilliams, M. L. 2020. Seasonal and Annual Variation in the Extent of Suitable Habitats for Forage Fishes in Chesapeake Bay, 2000-2016. Virginia Institute of Marine Science, William & Mary. https://doi.org/10.25773/dyjy-mm73.

Fabrizio, M. C., Tuckey, T. D., Smith, S. C., Ross, P. G., Snyder, R. A., Wang, H. V., and Bever, A. J. 2022. Characterization of Nursery Habitats used by Black Sea Bass and Summer Flounder in Chesapeake Bay and the Coastal Lagoons. Virginia Institute of Marine Science, William & Mary. doi: 10.25773/PJCC-RG41, https://scholarworks.wm.edu/reports/2837/.

Foden, W.B., Butchart, S.H.M., Stuart, S.N., Vié, J.C., Akçakaya, H.R., Angulo, A., et al. 2013. Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. PLoS ONE 8(6): e65427. https://doi.org/10.1371/journal.pone.0065427.

Hinson, K. E., Friedrichs, M. A., St-Laurent, P., Da, F., and Najjar, R. G. 2021. Extent and causes of Chesapeake Bay warming. JAWRA Journal of the American Water Resources Association.

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C., et al. 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography. 141, 227–238. doi: 10.1016/j.pocean.2015.12.014

IPCC 2014. Climate Change 2014: Synthesis Report. In Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Core Writing Team, Pachauri, R. K. and Meyer, L. A. 151pp. Geneva: IPCC.

IPCC. 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Core Writing Team, Masson Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Levitus, S., J.I. Antonov, J.L. Wang, et al. 2001. Anthropogenic warming of Earth's climate system. Science. 292: 5515: 267-270.

Maryland Department of Natural Resources. "Striped Bass Fishing Advisory." 2022. https://dnr.maryland.gov/fisheries/Documents/SB_Advisory_flyer.pdf

Mazzini, P. L., and Pianca, C. 2022. Marine Heatwaves in the Chesapeake Bay. Frontiers in Marine Science, 8(750265).

Meehl, G.A., and Thomas F. Stocker. 2007. Global Climate Projections. Intergovernmental Panel on Climate Change: Climate Change 2007: the Physical Science Basis. 747-845.

Najjar RG, Pyke CR, Adams MB, Breitburg D, Hershner C, Kemp M, Howarth R, Mulholland MR, Paolisso M, Secor D, Sellner K, Wardrop D, Wood R. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine, Coastal and Shelf Science 86(1):1-20.

National Marine Fisheries Service. 2022. State of the Ecosystem 2022: Mid-Atlantic. Retrieved: https://doi.org/10.25923/jd1w-dc26

Rice, K.C., and Jastram, J.D., 2015. Rising air and stream-water temperatures in Chesapeake Bay region, USA: Climatic Change, v. 128, p. 127-138 https://doi.org/10.1007/s10584-014-1295-9

Schonfeld, G., and Latour. 2022. Spatial differences in estuarine utilization by seasonally resident species in Mid-Atlantic Bight, USA. Fisheries Oceanography, https://onlinelibrary.wiley.com/doi/full/10.1111/fog.12611.

Shenk, G. W., Bhatt, G., Tian, R., Cerco, C.F., Bertani, I., and L. C. Linker. 2021. Modeling Climate Change Effects on Chesapeake Water Quality Standards and Development of 2025 Planning Targets to Address Climate Change. CBPO Publication Number 328-21, Annapolis, MD. 145 pp. https://www.chesapeakebay.net/channel_files/42671/p6modeldocumentation_climatechangedocumentation_(5).pdf.

Sutton-Grier, A., Wowk, K., and H. Bamford. 2015. Future of Our Coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. 51, 137-148. https://doi.org/10.1016/j.envsci.2015.04.006

Tassone, S., Besterman, A., Buelo, C., Ha, D., Walter, J., and M. Pace. 2022. Increasing heatwave frequency in streams and rivers of the United States. Limnology and Oceanography Letters. https://doi.org/10.1002/lol2.10284.

Tian, R., C.F. Cerco, G. Bhatt, L.C. Linker, and G.W. Shenk. 2021. Mechanisms Controlling Climate Warming Impact on the Occurrence of Hypoxia in Chesapeake Bay. Journal of the American Water Resources Association 1–21. https://doi.org/10.1111/1752-1688.12907.

Wagner, T., Midway, S., Whittier, J., DeWeber, J., and C. Paukert. 2017. Annual Changes in Seasonal River Water Temperatures in the Eastern and Western United States. Water 9(2), 90; https://doi.org/10.3390/w9020090.

Woodland, R., Houde, E. Lyubchich, V. 2022. Forage Indicator Development - Using Environmental Drivers to Assess Forage Status. Report submitted to the Chesapeake Bay Trust from the University of Maryland Center for Environmental Science Chesapeake Biological Laboratory, March 1, 2022. UMCES Project: CBL2021-038CBT, https://cbtrust.org/wp-content/uploads/Forage_Ind_FINAL_REPORT.pdf.

7. APPENDICES

Rising Watershed and Bay Water Temperatures—Ecological Implications and Management Responses

Appendix D
Synthesis Element 1 (Revised): Water Temperature Effects on Fisheries and Stream Health in Nontidal Waters

Synthesis Element 1 (Revised): Water Temperature Effects on Fisheries and Stream Health in Nontidal Waters

Abstract

A limited review of relevant scientific literature related to temperature sensitivities of fish species, stream health indicators, and any related geospatial information was conducted. Based on this review, we provide a syntheses of information related to nontidal waters in the Chesapeake Bay Rising stream temperatures will have a range of impacts on nontidal aquatic ecosystems. Cold headwaters and associated species like brook trout and sculpin are especially vulnerable to higher stream temperatures. Efforts could be taken to identify and protect high quality resilient cold headwater brook trout (Salvelinus fontinalis) habitat. More information on groundwater impacts on stream temperatures and ecologically relevant temperature thresholds for species of concern could help resource managers identify temperature resilient habitats and populations. A vulnerability assessment could be valuable to better understand the drivers and stressors of rising stream temperatures, their effects on aquatic resources, and the risk to fish and other aquatic species. Further research could help in developing and fully vetting a complete list of cold/cool water benthic macroinvertebrate taxa and freshwater mussel taxa that are vulnerable to temperature change in the Chesapeake watershed.

A. Contributors

Stephen Faulkner [a,*], Frank Borsuk [b], Greg Pond [b], Kevin Krause [c], Rosemary Fanelli [d], Matthew Cashman [e], Than Hitt [a], Benjamin Letcher [a]

[a] U.S. Geological Survey, Eastern Ecological Science Center, Kearneysville, West Virginia, 25430

[b] U.S. EPA Region III, Field Services Branch, Wheeling, WV 26003

[c] Minnesota Dept. of Natural Resources, St. Paul, MN

[d] U.S. Geological Survey, South Atlantic Water Science Center, Raleigh, NC, 27607

[e] U.S. Geological Survey, Maryland-Delaware-District of Columbia Water Science Center, Baltimore, MD 21228

[*] Corresponding author

Email address: faulkners@usgs.gov

B. Resources

The synthesis was developed through a limited review of the scientific literature and informal solicitation of expert opinion to formulate the overall approach and provide supporting science.

C. Approach

We conducted a limited review of the relevant scientific literature (key word search of ISI Web of Science and Google Scholar) and developed a questionnaire requesting information (Appendix 1) related to temperature sensitivities of fish species, stream health indicators, and any related geospatial information. This questionnaire was sent to a selected group of researchers, natural resource professionals, and other stakeholders in the Chesapeake Bay Watershed (CBW). Further informal discussions were held with respondents to the questionnaire who had recommended publications to include in this review.

D. Synthesis

Stream temperature has direct and indirect effects on many biological, physical, and chemical processes in the freshwater environment including significant impacts on fish metabolism, physiology, and behavior (Clark and Johnston, 1999). Climate change can also shift species ranges, distribution, phenology, and productivity modifying the emergent properties of an ecosystem with divergent preferences for habitat for cool-water and warm-water species (Staudinger et al. 2021; Weiskopf et al. 2020). Conservation and management decisions regarding aquatic systems face new challenges as future temperature are projected to rise markedly and flow timing is projected to shift for many watersheds in the Northeast United States under climate change impacts (Isaak et al. 2015; Paukert et al. 2021).

Synthesizing the effects of water temperature on stream health in nontidal waters of the CBW is a complicated undertaking given the wide diversity of habitats, species, potential responses, and the limited number of studies directly measuring the effects of water temperature. The myriad of cool and coldwater fish communities are facing unique threats due to increasing water temperatures in conjunction with other stressors (Frumhoff et al. 2007). While not covered in this chapter, similar temperature-related impacts have been documented for amphibians (Blaustein et al. 2010; Polo-Cavia et al. 2017; Miller et al. 2018) and lake ecosystems (Breeggemann et al. 2016).

Fish

Temperature effects on freshwater fish have been studied in earnest since the 1940's (Eaton et al. 1995) across a range of different aspects including lethal limits (Hart, 1947), reproduction (Gaston et al. 2017), physiology (Alfonso et al. 2020), and life stage (Turschwell et al., 2017). However, linking broad implications from general principles or mensurative studies to more specific relationships that can inform Chesapeake Bay management and mitigation decisions is more difficult. Every species has a thermal optimum and maximum, but specific responses vary by life stage, length of exposure, and interactions with other stressors (Timm et al., 2020) and data specific to Chesapeake Bay species are limited. Few previous studies have focused on how climate change may impact headwater systems, despite the importance of these areas for aquatic refugia.

The paucity of species/taxa-specific studies globally means that climate impact assessments may need to focus on conservation of ecological systems at broad levels with results that may not be readily translatable into useful and actionable information for managers/practitioners on the ground. A recent literature review of multiple stressors driving biological impairment of CBW freshwater streams found that only about half of the studies reviewed (34) included temperature and it was identified as an important stressor in about 30% of those studies (Fanelli et al., 2022).

The U.S. Environmental Protection Agency surveys streams and rivers and compiles the information, including stream temperatures, in the National Rivers and Streams Assessment (hereafter NRSA) (USEPA, 2020). As part of a larger fish habitat assessment within the CBW, Krause et al. (2021a) collated species occurrence data from a suite of natural resource agencies and other stakeholders. These data were cross-referenced with the EPA NRSA data set to identify the stream temperature classification of Chesapeake Bay freshwater species. Brown trout (*Salmo trutta*), brook trout, and rainbow trout (*Oncorhynchus mykiss*) are the only species identified as coldwater (Table 1). Checkered sculpin (*Cottus* sp. cf. *girardi*), an undescribed global endemic species, also is limited to cold groundwater-fed streams in the Chesapeake Bay headwaters (central Potomac River basin). Krause et al. (2021b) have developed species occurrence maps for the species of primary importance, sculpin, and brook trout. These maps provide a scalable geospatial resource to identify where the species occur in the watershed and can be linked to other data, e.g., Hydrologic Unit Code (HUC) classification, climate change scenarios, necessary to identify areas vulnerable to increasing water temperatures (Fig 1).

Brook trout are specifically identified as one of the four indicator species in the Chesapeake Bay Executive Order No. 13508 (2009) because “they reflect the habitat health and hold great ecological, commercial and recreational significance”. This species relies on clean, cold stream habitat and is sensitive to rising stream temperatures, thus providing a potential early warning of detrimental changes in water quality (Hitt et al. 2017). Brook trout are also highly prized by recreational anglers and have been designated as the state fish in nine states (MI, NH, NJ, NY, NC, PA, VT, VA, and WV). This species is an essential part of the headwater stream ecosystem, an important part of the upper watershed’s natural heritage and a valuable recreational resource (Hudy et al. 2008). The decline of brook trout serves as a warning about the health of local waterways and the impact of activity on lands draining to them (Chesapeake Bay Executive Order No. 13508, 2009). More than a century of declining brook trout populations has led to lost economic revenue and recreational fishing opportunities in the Bay’s headwaters.

Because of their importance to the region and sensitivity to higher stream temperatures, brook trout and the headwater streams they occupy have been the subject of intensive research with a focus on understanding the effects of air temperature on water temperature and resultant impact on brook trout habitat (Flebbe et al. 2006; Snyder et al. 2015). There are, however, other factors that can mitigate the impact and response of simple changes in air temperature including land use (Merriam et al. 2019; Maloney et al. 2020), landform features (Johnson et al. 2017), stream flow (Merriam et al. 2017), and fine-scaled groundwater inputs (Snyder et al. 2015; Briggs et al. 2018). In addition, spatial grain or scale is an important aspect affecting the results and interpretations. For example, Flebbe at al. (2006) used a watershed model approach, which assumes one uniform value of thermal sensitivity for the entire watershed, and predicted a nearly 80% loss of suitable brook trout habitat under a 3.0 ^{o}C temperature increase. Snyder et al. (2015) used a reach model incorporating fine-scaled groundwater inputs which reduced the loss of suitable brook trout habitat under a 3.0 ^{o}C temperature increase to approximately 20% from the 2012 baseline. Introduced fishes also may compete with and displace native brook trout (Fausch and White 1981 ; Wagner et al. 2013) and detrimental impacts may increase with elevated stream temperature (Hitt et al. 2017).

There are several models developed to predict stream temperatures and brook trout occupancy to provide managers and researchers the decision-support tools needed to better understand impacts to brook trout from changes in climate and land use. Deweber and Wagner (2014) developed a neural network model to predict daily mean water temperature in brook trout streams throughout their native range. Trout Unlimited has developed a conservation portfolio approach that incorporates the Deweber and Wagner model and evaluates brook trout populations based on ability to recover from disturbances (resiliency), occurrence of multiple populations on the landscape (redundancy), and the genetic, life history, and geographic diversity (representation) (Fesenmyer et al. 2017, Fig. 2A). Other data visualization and decision support tools have been developed to assist natural resource managers with decisions related to brook trout management and conservation (MD DNR 2022, Fig. 2B; Eastern Brook Trout Joint Venture 2022, Fig. 2C.)

Letcher et al. (2016) have developed a Bayesian model to predict daily stream temperature based on catchment characteristics and climate conditions. That temperature model underpins a dynamic interactive data visualization tool, the Interactive Catchment Explorer (ICE), for exploring catchment characteristics, model predictions, and identifying priority catchments (Walker et al. 2020). It provides resource managers and researchers the ability to explore complex, multivariate environmental datasets by selecting specific variables and filters to identify spatial patterns and prioritize locations for restoration or further study. Figure 3 depicts predicted changes in occupied brook trout habitat within northeastern United States with a 4.0 ^{o}C temperature increase. Predictions in ICE can be viewed as a first cut for locations without stream temperature data as it is difficult to incorporate local drivers with insufficient data in regional temperature models (e.g., the buffering effects of groundwater-surface water interactions).

Table 1. Adapted National Rivers and Streams Assessment (NRSA) classification of cold (CD) and cool (CL) water temperature Chesapeake Bay freshwater fish species (adapted from EPA, 2020)

Common Name	NRSA Classification		Common Name	NRSA Classification	Common Name	NRSA Classification
SLIMY SCULPIN	CD		SHORTHEAD REDHORSE	CL	BLUEBACK HERRING	CL
BROWN TROUT	CD		POTOMAC SCULPIN	CL	ALEWIFE	CL
BROOK TROUT	CD		BLUE RIDGE SCULPIN	CL	AMERICAN PICKEREL	CL
RAINBOW TROUT	CD		REDSIDE DACE	CL	BRIDLE SHINER	CL
SHIELD DARTER	CL		CHAIN PICKEREL	CL	MOUNTAIN REDBELLY DACE	CL
ROSYFACE SHINER	CL		SWALLOWTAIL SHINER	CL	BANDED SCULPIN	CL
MOTTLED SCULPIN	CL		ALLEGHENY PEARL DACE	CL	ROANOKE HOG SUCKER	CL
RAINBOW DARTER	CL		STONECAT	CL	LONGFIN DARTER	CL
LOGPERCH	CL		BLACKNOSE SHINER	CL	RIVERWEED DARTER	CL
FANTAIL DARTER	CL		BROOK STICKLEBACK	CL	CANDY DARTER	CL
TONGUETIED MINNOW	CL		AMERICAN EEL	CL	NEW RIVER SHINER	CL
LONGHEAD DARTER	CL		YELLOW PERCH	CL	CHANNEL DARTER	CL
BLACKSIDE DARTER	CL		BANDED KILLIFISH	CL	APPALACHIA DARTER	CL
W. BLACKNOSE DACE	CL		WALLEYE	CL	KANAWHA MINNOW	CL
VARIEGATE DARTER	CL		MUSKELLUNGE	CL	BLACKCHIN SHINER	CL
BANDED DARTER	CL		SEA LAMPREY	CL	NORTHERN REDBELLY DACE	CL
SILVER SHINER	CL		NORTHERN PIKE	CL	RUDD	CL
MIMIC SHINER	CL		AMERICAN SHAD	CL	HICKORY SHAD	CL
FALLFISH	CL		EMERALD SHINER	CL	BLUEFISH	CL
COMELY SHINER	CL		NORTHERN BROOK LAMPREY	CL		
SPOTFIN SHINER	CL		TROUT-PERCH	CL		
SPOTTAIL SHINER	CL		GLASSY DARTER	CL		
REDBREAST SUNFISH	CL		SWAMP DARTER	CL		

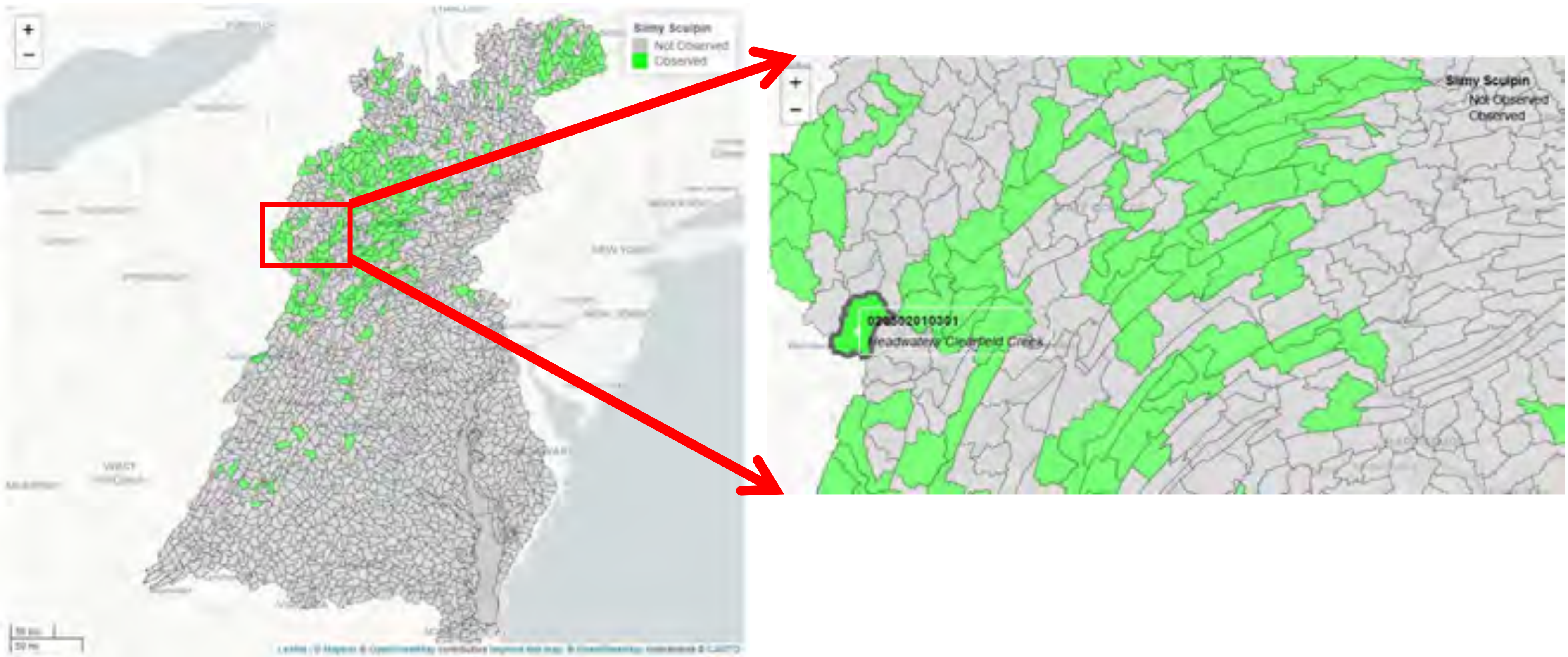


Figure 1. Slimy sculpin (*Cottus cognatus*) fish occurrence map for the Chesapeake Bay Watershed
Soure: Krause et al. 2021b

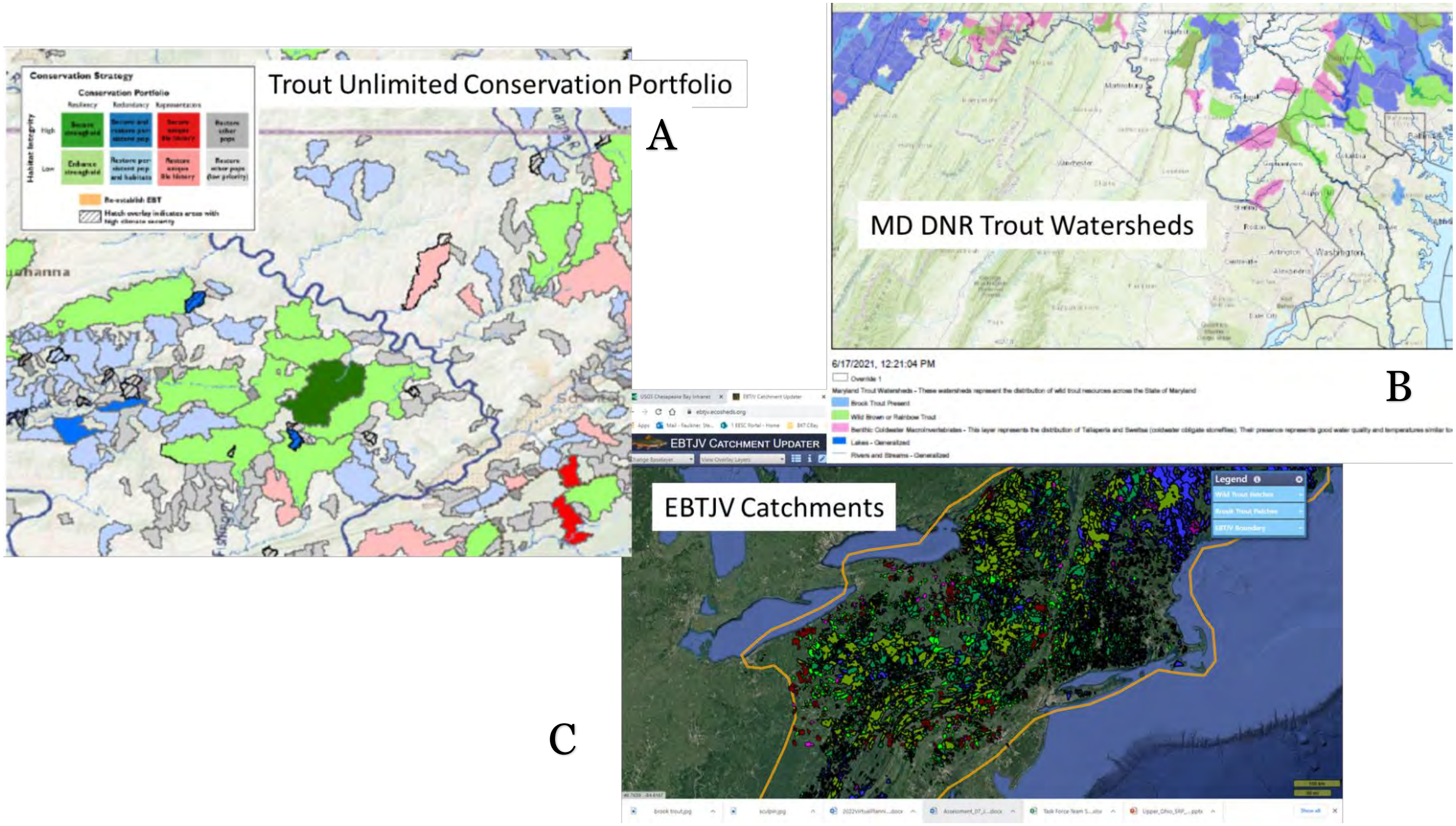
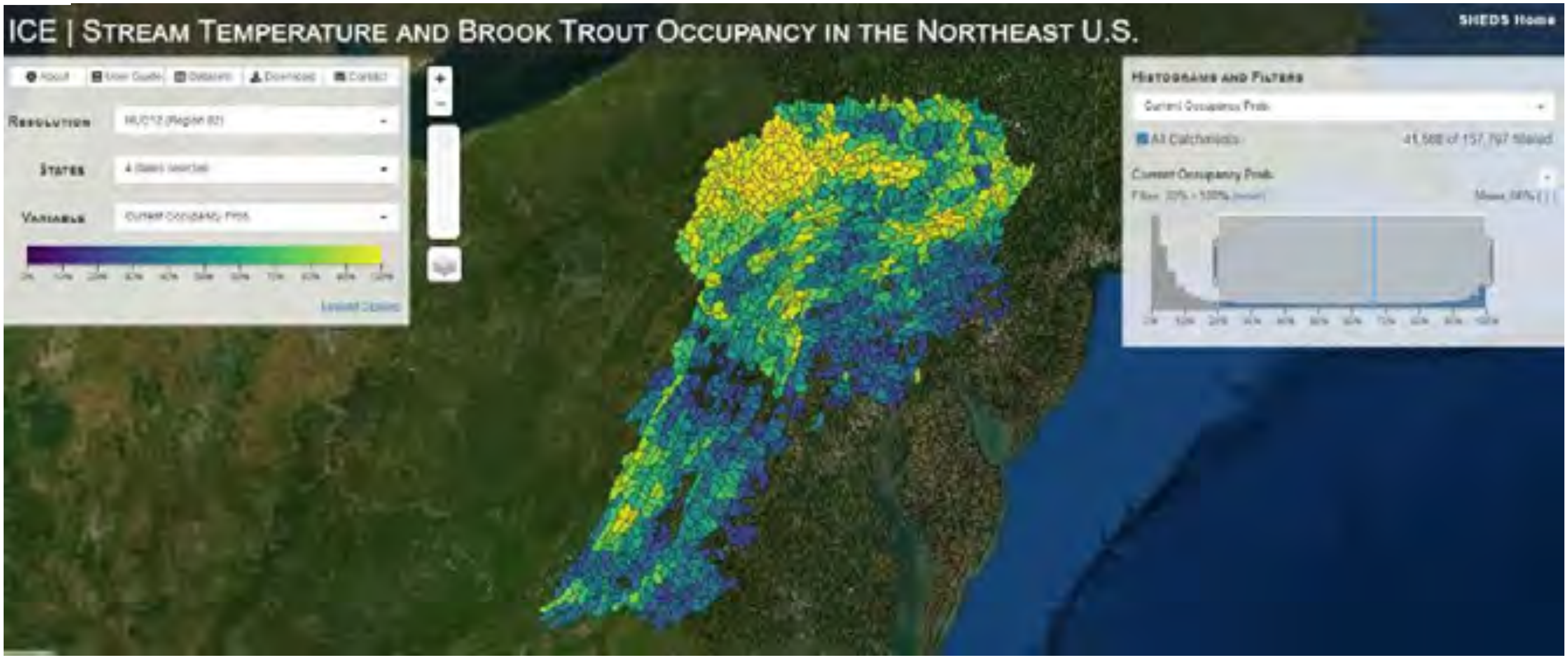


Figure 2. Examples of spatially explicit brook trout decision support tools. (A) Trout Unlimited conservation portfolio (Fesenmyer et al. 2017); (B) Maryland Department of Natural Resources (MD DNR 2022) trout watersheds mapping tool; (C) Eastern Brook Trout Joint Venture (2022) Catchments

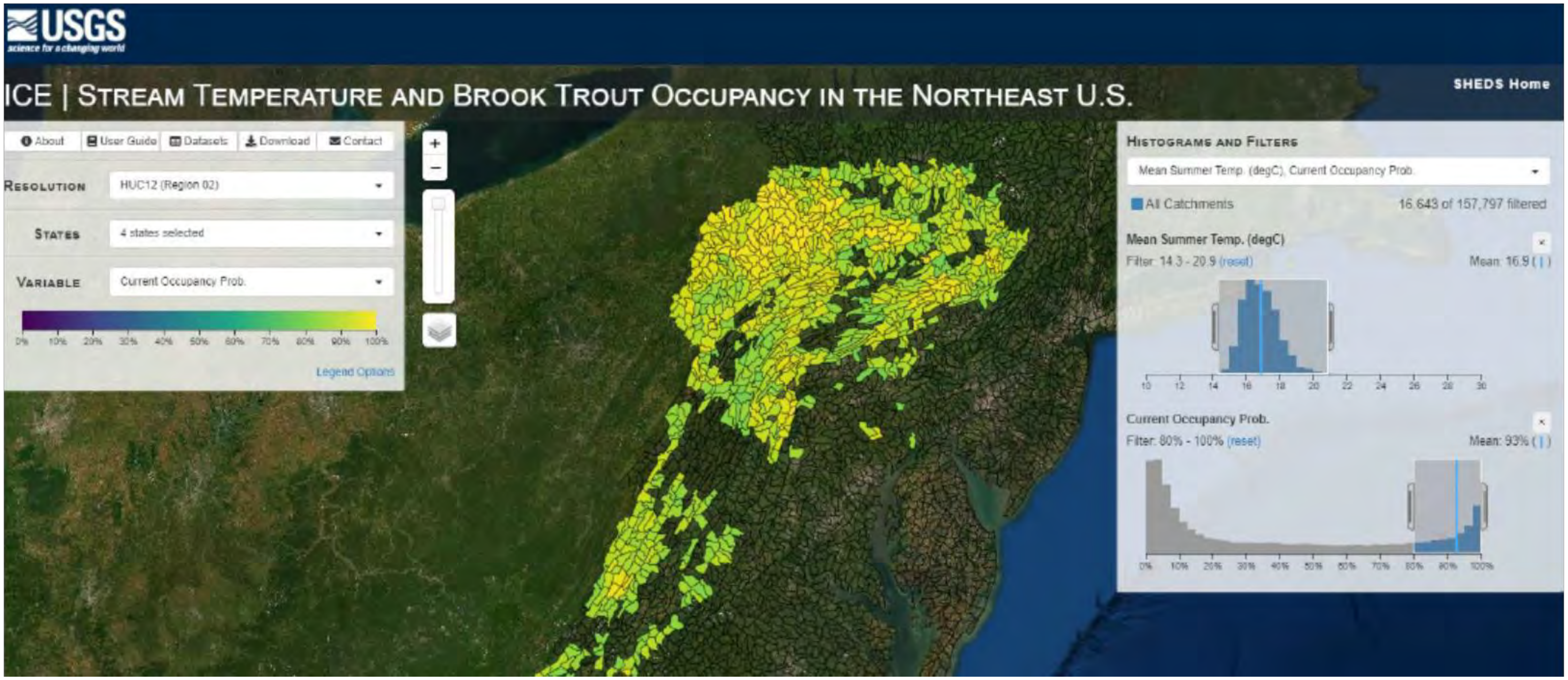
Brook Trout Occupancy in MD, PA, VA, and WV

A



B

Catchments in MD, PA, WV, VA with 80-100% Occupancy Probability



C

Occupancy Probability with +4 °C Air Temperature

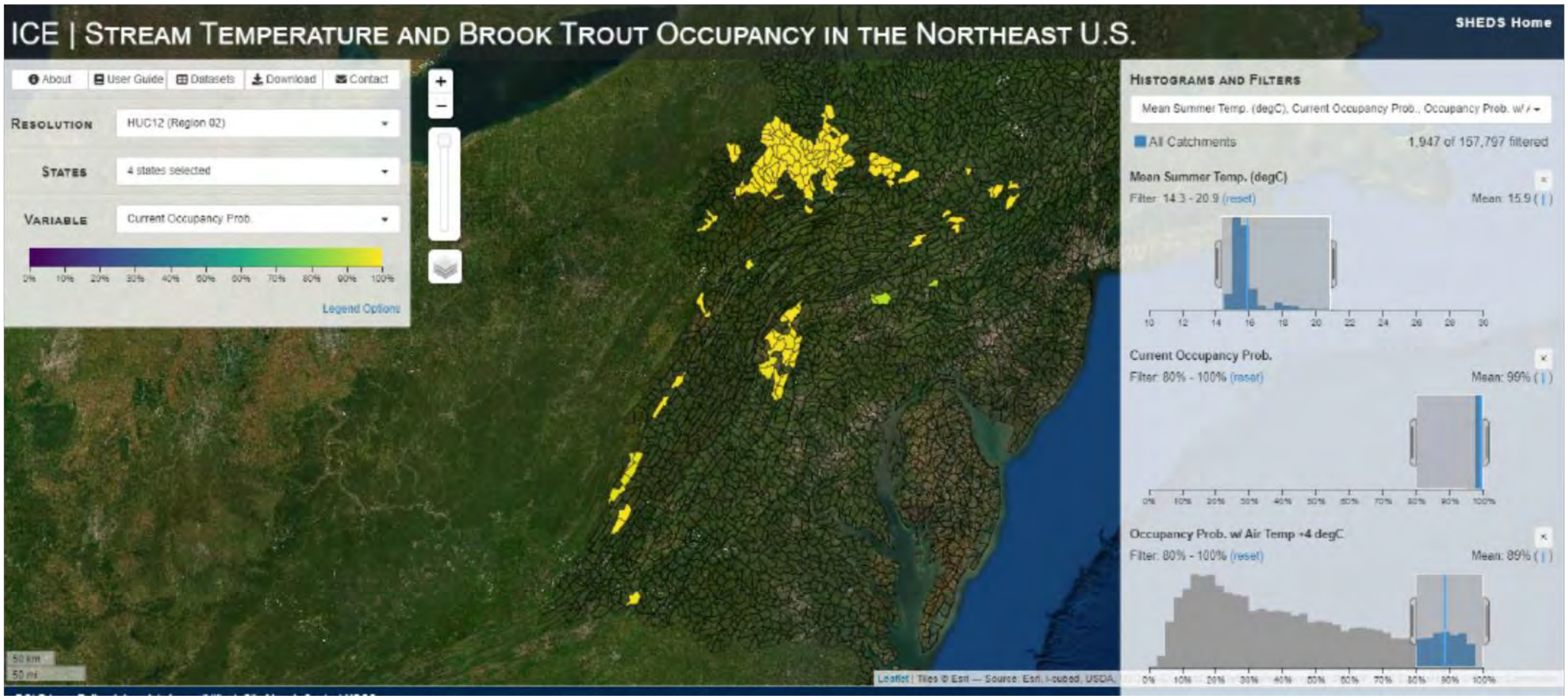


Figure 3. Examples of effects of rising air temperature on occupied brook trout habitat using the Interactive Catchment Explorer (ICE) (Walker et al. 2020, www.usgs.gov/apps/ecosheds/ice-northeast) for Maryland, Pennsylvania, Virginia, and West Virginia. 3A - current brook trout occupied habitat (20-80% probability); 3B - current brook trout occupied habitat (80-100% probability); 3C - predicted brook trout occupied habitat (80-100% probability) with a 4 ^{0}C rise in air temperature.

Macroinvertebrates/Mussels

Like fishes and macroinvertebrates, freshwater mussels are partially structured by temperature where species occupy niches under thermal optima and threshold constraints. Nearly 70% of the 297 species of the freshwater mussel family Unionidae in North America are extinct or vulnerable to extinction (Bogan, 1993). Several factors (habitat degradation, water quality, temperature, etc.) are playing a role in the decline of the freshwater mussels. Recent findings suggest that many freshwater mussel species in the Southeastern United States are already living close to their upper thermal tolerances (Pandolfe et al. 2012; Martin 2016; Barnett and Woolnough 2021).While water temperature controls basic metabolic processes and dissolved oxygen availability, it also effects the timing of important life history stages in both larval and adult development, emergence, egg laying, and overall population recruitment and maintenance. Further, a myriad of direct and indirect ecosystem-level processes and stressors can be affected by climate change, thereby altering macroinvertebrate community structure. Thus, while cold water stenotherms and warmwater eurytherms have evolved mechanisms to proliferate differently under both narrow and wide physiologic temperature ranges, other environmental stressors will be exacerbated leading to further assemblage alteration (Smith et al. 2017). In the Chesapeake Bay watershed, stream size, latitude, and elevation exert overarching spatial controls on natural thermal regimes and the resulting macroinvertebrate fauna. Predictably, we would expect shifts in macroinvertebrate assemblages to occur with increased warming. Hypothetically, coldwater and coolwater specialists could face inhospitable future conditions and local extirpation where stenothermic taxa would be forced to shift toward other habitats along the river continuum (e.g., higher elevation or smaller groundwater-fed streams).

One key problem in monitoring and assessing the effects of temperature change is in assigning definitive thermal traits to macroinvertebrate taxa. States like Maryland have identified several coldwater specialist taxa, mainly mayflies (Ephemeroptera), stoneflies (Plecoptera) , and caddisflies (Trichoptera) (or EPT) via continuous temperature data where others have often used other modeling methods or best professional judgment. Existing trait-based assignments for genera (e.g., Vieria et al. 2006; Poff et al. 2006, USEPA 2016) are helpful resources but species-level identification is needed among some genera (USEPA 2016). However, out of the >650 genera compiled for the Chesapeake Bay watershed (Smith et al. 2017), nearly 100 genera are listed as coldwater stenotherms (USEPA 2016); this list provides a potential means to design appropriate analyses to track climate change and predict outcomes. In comparing MD, PA, and trait-based thermal designations, some disparity exists USEPA 2016 (Table 2). In this list below, many other Mid-Atlantic taxa (e.g., additional EPT, Chironomidae and other Diptera, aquatic beetles, and crustaceans) are not listed. Further work could help in developing and fully vetting a more complete list of cold/cool water taxa that are vulnerable to temperature change in the Chesapeake watershed. Going forward, monitoring for individual indicator taxa could be critical, but whole assemblage assessments could provide stronger evidence of shifting spatial patterns.

Table 2. Comparison of thermal trait-based assignments for macroinvertebrate taxa in the states of Maryland (MD) and the state of Pennsylvania (PA) (adapted from Poff et al., 2006; USEPA 2016).

Order	Genus	MD	PA	Poff et al. (2006, EPA (2016)
Diptera	*Bittacomorpha*	Cold		Cold
Diptera	*Dixa*	Cold		Cold/Cool
Diptera	*Heleniella*	Cold		Cold
Diptera	*Prodiamesa*	Cold		Cold
Ephemeroptera	*Ameletus*		Cold	Cold
Ephemeroptera	*Cinygmula*	Cold	Cold	Cold
Ephemeroptera	*Diphetor*	Cold	Cold	Cold/Cool
Ephemeroptera	*Drunella*		Cold	Cold/Cool
Ephemeroptera	*Epeorus*	Cold	Cool	Cold
Ephemeroptera	*Ephemera*	Cold		Cold/Cool
Ephemeroptera	*Ephemerella*		Cold	Cold/Cool
Ephemeroptera	*Eurylophella*		Cold	Cold/Cool
Ephemeroptera	*Habrophlebia*	Cold	Cool	Cold
Ephemeroptera	*Paraleptophlebia*	Cold		Cold/Cool
Plecoptera	*Alloperla*	Cold	Cold	Cold
Plecoptera	*Amphinemura*		Cold	Cold/Cool
Plecoptera	*Diploperla*		Cold	Cold
Plecoptera	*Haploperla*		Cold	Cold/Cool
Plecoptera	*Isoperla*		Cold	Cold/Cool
Plecoptera	*Leuctra*	Cold		Cold/Cool
Plecoptera	*Malirekus*		Cold	Cold
Plecoptera	*Peltoperla*		Cold	Cold/Cool
Plecoptera	*Pteronarcys*		Cold	Cold/Cool
Plecoptera	*Remenus*		Cold	Cold
Plecoptera	*Sweltsa*	Cold	Cold	Cold/Cool
Plecoptera	*Tallaperla*	Cold	Cold	Cold/Cool
Plecoptera	*Yugus*		Cold	Cold
Trichoptera	*Diplectrona*	Cold		Cold
Trichoptera	*Wormaldia*	Cold	Cold	Cold/Cool

A need exists to develop a strategy to obtain and classify the thermal tolerance information on the resident freshwater mussels within the Chesapeake Bay watershed as this information is currently limited. Wood et al. (2021) has summarized the status and distribution of the freshwater mussels of the Chesapeake Bay watershed (Table 3). A next step in this summation is to review the scientific literature and assign upper thermal limits for each species within the Chesapeake Bay watershed. Martin (2016) developed a laboratory method that could be used to determine the upper thermal limits of specific species. A similar effort to Wood et al. (2021) was convened by the Ohio River Valley Water Sanitation Commission (ORSANCO) (2022) to assign temperature criteria limits to the 160 species of fishes in the Ohio River. A similar effort could be completed for the freshwater mussels.

Table 3. Status and Distribution of the Freshwater Mussel of the Chesapeake Bay watershed (Virginia, Maryland, District of Columbia, Delaware, West Virginia, and Pennsylvania) (Wood et al. 2021). YES indicates the historic records of the species exists within the bay drainage of the state, or within the basin listed. NO indicates, the species does not exist in the bay drainage of the state (although it may exist in the state outside the bay drainage). Totals by state are the number of species with YES designation.

Genus	Species	Common Name	Federal Status	VA	MD	DC	DE	WV	PA	NY
Alasmidonta	*heterodon*	Dwarf Wedgemussel		YES	YES	YES	YES	NO	YES	NO
Alasmidonta	*undulata*	Triangle Floater		YES	YES	YES	YES	YES	YES	YES
Alasmidonta	*varicosa*	Brook Floater		YES	YES	YES	YES**	YES	YES	YES
Alasmidonta	*marginata*	Elktoe		NO	NO	NO	NO	NO	YES	YES
Utterbackiana (previously Anodonta)	*implicata*	Alewife Floater		YES	YES	YES	YES	NO	YES	NO
Anodontoides	*ferussacianus*	Cylindrical Papershell		NO	NO	NO	NO	NO	YES	YES
Elliptio	*complanata*	Eastern Elliptio		YES	YES	YES	YES	YES	YES	YES
Elliptio	*congaraea*	Carolina Slabshell		YES	NO	NO	NO	NO	NO	NO
Elliptio	*fisheriana*	Northern Lance		YES	YES	YES	YES	YES	YES	NO
Elliptio	*Icterina*	Variable Spike		YES	NO	NO	NO	NO	NO	NO
Elliptio	*lanceolata*	Yellow Lance		YES	YES	NO	NO	NO	NO	NO
Elliptio	*producta*	Atlantic Spike		YES	YES	NO	NO	NO	NO	NO
Elliptio	*roanokensis*	Roanoke Slabshell		YES	NO	NO	NO	NO	NO	NO
Elliptio	*angustata*	Carolina Lance		YES	NO	YES	NO	NO	NO	NO
Fusconaia	*masoni*	Atlantic Pigtoe		YES	NO	NO	NO	NO	NO	NO
Lampsilis	*cardium/ovata*	Pocketbook		YES	YES	NO	NO	NO	YES	NO
Lampsilis	*cariosa*	Yellow Lampmussel		YES	YES	YES	YES	YES	YES	YES
Lampsilis	*radiata*	Eastern Lampmussel		YES	NO	YES	YES	YES	YES	YES
Lasmigona	*compressa*	Creek heelsplitter		NO	NO	NO	NO	NO	NO	YES
Lasmigona	*subviridis*	Green Floater		YES	YES	YES	YES**	YES	YES	YES
Leptodea	*ochracea*	Tidewater Mucket		YES	YES	YES	YES	NO	NO	NO
Ligumia	*nasuta*	Eastern Pondmussel		YES	YES	YES	YES	YES	NO	NO
Margaritifera	*margaritifera*	Eastern pearlshell		NO	NO	NO	NO	NO	NO	YES
Pleurobema	*collina*	James Spinymussel		YES	NO	NO	NO	YES	NO	NO
Pyganodon	*cataracta*	Eastern Floater		YES	YES	YES	YES	YES	YES	YES
Pyganodon	*grandis*	Giant floater		NO	NO	NO	NO	NO	NO	YES*
Strophitus	*undulatus*	Creeper		YES	YES	YES	YES	YES	YES	YES
Utterbackia	*imbecillis*	Paper Pondshell		YES	YES	YES	NO	YES	YES	YES

	: Expected Extinct
	: Endangered
	: Threatened

	Bay Watershed	VA	MD	DC	DE	WV	PA	NY
TOTAL:	28	23	16	15	11	12	15	13

**Giant floater is not expected to occur in the Upper Susquehanna basin, however NYSDEC found individuals in the Canisteo River that clearly had nodulous beak sculpture like we would expect with giant floater. Right next to these other individuals were observed with non-nodulous beak sculpture (we called these eastern floater) and still others with one nodulous valve and none non-nodulous valve. Acknowledging uncertainty, NYSDEC has been lumping all questionable records as Pyganodon sp.*
***Brook Floater and Green Floater are expected to be locally extinct from Delaware waters but historic records have been observed.*

E. Evaluation

Given the limited data at present for specific mitigation efforts and uncertainty of future climate scenarios and impacts, the conceptual framework developed by Foden et al. (2013) provides an approach for identifying the species most vulnerable to extinction from a range of climate change induced stresses (Fig 4.). The framework guides users to independently measure three dimensions of climate change vulnerability, namely sensitivity (the lack of potential for a species to persist in situ), exposure (the extent to which each species' physical environment will change) and low adaptive capacity (a species' inability to avoid the negative impacts of climate change through dispersal and/or microevolutionary change). The three dimensions can then be used to allocate species to one of four classes of climate change vulnerability, each with different implications for conservation (Figure 1). Species are considered highly vulnerable to climate change if they qualify as highly sensitive, highly exposed and with limited adaptive capacity.

Ultimately, a vulnerability assessment (sensu Hare et al. 2016) could be beneficial to better understand the drivers and stressors of rising stream temperatures, their effects on aquatic resources, and the risk to fish and other aquatic species (Fig 5).

F. Bibliography

Alfonso, S., Gesto, M. and Sadoul, B., 2021. Temperature increase and its effects on fish stress physiology in the context of global warming. Journal of Fish Biology, 98(6), pp.1496-1508.

Barnett, S.E.; Woolnough, D.A. Variation in Assemblages of Freshwater Mussels Downstream of Dams and Dam Removals in the Lake Michigan Basin, Michigan, USA. Diversity 2021, 13, 119. https://doi.org/10.3390/d13030119

Blaustein, Andrew R., Susan C. Walls, Betsy A. Bancroft, Joshua J. Lawler, Catherine L. Searle, and Stephanie S. Gervasi. 2010. Direct and Indirect Effects of Climate Change on Amphibian Populations. Diversity 2: 281-313. https://doi.org/10.3390/d2020281

Bogan, A.E. 1993. Freshwater Bivalve Extinctions (Mollusca: Unionoida): A Search for Causes, American Zoologist. 33(6): 599–609. https://doi.org/10.1093/icb/33.6.599

Breeggemann, J.J., Kaemingk, M.A., DeBates, T.J., Paukert, C.P., Krause, J.R., Letvin, A.P., Stevens, T.M., Willis, D.W. and Chipps, S.R. (2016), Potential direct and indirect effects of climate change on a shallow natural lake fish assemblage. Ecol Freshw Fish, 25: 487-499. https://doi.org/10.1111/eff.12248

Briggs, M.A., J.W. Lane, C.D. Snyder, E.A. White, Z.C. Johnson, D.L. Nelms and N.P. Hitt. 2018. Shallow bedrock limits groundwater seepage-based headwater climate refugia. Limnologica 68:42-156.

Clarke, A.; Johnston, N. M. 1999. Scaling of metabolic rate with body mass and temperature in teleost fish. Journal of Animal Ecology, 68, 893–905.

DeWeber, J. T., & Wagner, T. 2014. A regional neural network ensemble for predicting mean daily river water temperature. J. Hydrology 517:187–200.

Eastern Brook Trout Joint Venture. 2022. EBTJV Catchment Updater https://ebtjv.ecosheds.org/# [accessed January 6, 2022]

Eaton, J.G., J.H. McCormick, B.E. Goodno, D.G. O"Brien, H.G. Stefany, M. Hondzo, and R. R.M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries 20:10-18.

Executive Order No. 13508, 74 Fed. Reg. 93 (May 15, 2009).

Fanelli, R.M., M. J. Cashman and A. J. Porter. 2022. Identifying key stressors driving biological impairment in freshwater streams in the Chesapeake Bay watershed, USA. Environmental Management 70:926-949.

Fausch, K. D., and R. J. White. 1981. Competition between brook trout and brown trout for positions in a Michigan stream. Canadian Journal of Fisheries and Aquatic Sciences 38:1220–1227.

Fesenmyer, K.A., A.L. Haak, S.M. Rummel, M. Mayfield, S.L. McFall, and J.E. Williams. 2017. Eastern Brook Trout Conservation Portfolio, Range-wide Habitat Integrity and Future Security Assessment, and Focal Area Risk and Opportunity Analysis. Final report to National Fish and Wildlife Foundation. Trout Unlimited, Arlington, Virginia.

Flebbe, P. A., L. D. Roghair, and J. L. Bruggink. 2006. Spatial modeling to project southern Appalachian trout distribution in a warmer climate. Transactions of the American Fisheries Society 135:1371–1382.

Foden WB, Butchart SHM, Stuart SN, Vie´ J-C, Akcakaya HR, et al. (2013) Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. PLoS ONE 8(6): e65427. doi:10.1371/journal.pone.0065427

Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, D.J. Wuebbles. 2007. Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions. Synthesis report of the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS).

Gaston, K. J., Butlin, R. K., & Snook, R. R. (2017). Local adaptation of reproductive performance during thermal stress. Journal of Evolutionary Biology, 30, 422–429.

Hare JA, Morrison WE, Nelson MW, Stachura MM, Teeters EJ, Griffis RB, et al. (2016) A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. PLoS ONE 11(2): e0146756. doi:10.1371/ journal.pone.0146756

Hart, J.S. 1947. Lethal temperature relations of certain fish in the Toronto Region. Trans. Royal Soc. Can. (Section 5) 41:57-71.

Hitt, N.P., E. Snook and D. Massie. 2017. Brook trout use of thermal refugia and foraging habitat influenced by brown trout. Canadian Journal of Fisheries and Aquatic Sciences 74:406-418.

Hudy, M., T. M. Thieling, N. Gilles, and E. P. Smith. 2008. Distribution, status, and land use characteristics of subwatersheds within the native range of brook trout in the eastern United States. North American Journal of Fisheries Management 28:1069–1085.

Isaak, D.J., Young, M.K., Nagel, D.E., Horan, D.L. and Groce, M.C. 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. Glob Change Biol, 21: 2540-2553. https://doi.org/10.1111/gcb.12879

Johnson, Z.C., Snyder, C.D., Hitt, N.P., 2017. Landform features and seasonal precipitation predict shallow groundwater influence on temperature in headwater streams. Water Resour. Res. 53:5788–5812.

Krause, K.P., and Maloney, K.O., 2021a, Community metrics from inter-agency compilation of inland fish sampling data within the Chesapeake Bay Watershed: U.S. Geological Survey data release, https://doi.org/10.5066/P9D6JU4X.

Krause, K. P. and K.O. Maloney 2021b. Map of fish species observations from inland Chesapeake Bay Watershed fish samples. https://d18lev1ok5leia.cloudfront.net/usgs/fhat/FishSpeciesObservations_InlandChesapeakeBayWatershed.html.

Letcher, B.H.; Hocking, D.J.; O'Neil, K.; Whiteley, A.R.; Nislow, K.H.; O'Donnell, M.J. 2016. A hierarchical model of daily stream temperature using air-water temperature synchronization, autocorrelation, and time lags. PeerJ 2016, 4, e1727

Maloney, K. O., Krause, K. P., Buchanan, C., Hay, L. E., McCabe, G. J., Smith, Z. M., and Young, J. A. 2020. Disentangling the potential effects of land-use and climate change on stream conditions. Global change biology, 26(4), 2251-2269.

Maryland DNR. 2022. Maryland DNR Freshwater Fisheries - Coldwater Resources Mapping Tool https://maryland.maps.arcgis.com/apps/webappviewer/index.html?id=dc5100c0266d4ce89df813f34678944a [accessed January 6, 2022]

Martin, K.R.C. 2016. Upper Thermal Limits of Freshwater Mussels (Bivalvia, Unionoida) In Ramped Temperature Exposures. Missouri State University Graduate Theses. 2969. https://bearworks.missouristate.edu/theses/2969

Merriam, E. R., R. Fernandez, J. T. Petty, and N. Zegre. 2017. Can brook trout survive climate change in large rivers? If it rains. Sci. Tot. Environ: 607–608:1225–1236

Merriam, E. R., J. T. Petty, and J. Clingerman. 2019. Conservation planning at the intersection of landscape and climate change: brook trout in the Chesapeake Bay watershed. Ecosphere 10(2) e02585. https ://doi.org/10.1002/ecs2.2585

Miller, D.A.W., Grant, E.H.C., Muths, E. et al. 2018. Quantifying climate sensitivity and climate-driven change in North American amphibian communities. Nat Commun 9:3926. https://doi.org/10.1038/s41467-018-06157-6

Ohio River Valley Water Sanitation Commission 2022. https://www.orsanco.org/wp-content/uploads/2016/11/Updating-a-temperature-criteria-methodology-for-the-Ohio-River-mainstem.pdf [accessed January 19, 2023]

Pandolfe, TJ, TJ. Kwak, and G Cope. 2012. Thermal tolerances of freshwater mussels and their host fishes: Species Interaction in a changing climate. Freshwater Mollusk Biology and Conservation 15(1): 69-82. https://doi.org/10.31931/fmbe.v15i1.2012.69-82

Paukert, C., Olden, J.D., Lynch, A.J., Breshears, D.D., Christopher Chambers, R., Chu, C., Daly, M., Dibble, K.L., Falke, J., Issak, D., Jacobson, P., Jensen, O.P. and Munroe, D. (2021), Climate Change Effects on North American Fish and Fisheries to Inform Adaptation Strategies. Fisheries, 46: 449-464. https://doi.org/10.1002/fsh.10668

Polo-Cavia, N., Boyero, L., Martín-Beyer, B., Barmuta, L.A. and Bosch, J. 2017. Joint effects of rising temperature and the presence of introduced predatory fish on montane amphibian populations. Anim Conserv, 20: 128-134. https://doi.org/10.1111/acv.12294

Poff NL, Olden JD, Vieira NK, Finn DS, Simmons MP, Kondratieff BC (2006) Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships J N Am Benthol Soc 25(4):730-755

Smith, Zachary M., Claire Buchanan, and Andrea Nagel. 2017. Refinement of the Basin-Wide Benthic Index of Biotic Integrity for Non-Tidal Streams and Wadeable Rivers in the Chesapeake Bay Watershed. ICPRB Report 17-2. Interstate Commission on the Potomac River Basin, Rockville, MD.

Snyder, C.D., N.P. Hitt and J.A. Young. 2015. Accounting for the influence of groundwater on thermal sensitivity of headwater streams to climate change. Ecological Applications 25:1397-1419.

Staudinger, MD, Lynch, AJ, Gaichas, S, Fox, M, Gibson-Reinemer, D, Langan, JA, Teffer, AK, Thackeray, SJ, Winfield, IJ. 2021. How does climate change affect emergent properties of aquatic ecosystems? Fisheries, 46:423-441. **https://doi.org/10.1002/fsh.10606**

Timm A., V. Ouelle, and M. Daniels M. 2020. Swimming through the urban heat island: Can thermal mitigation practices reduce the stress? River Res Applic. 36:1973–1984.

Turschwell, M. P., Balcombe, S. R., Steel, E. A., Sheldon, F., and Peterson, E. E. 2017. Thermal habitat restricts patterns of occurrence in multiple life-stages of a headwater fish. Freshwater Science, 36:402–414.

U.S. EPA (Environmental Protection Agency). (2016) Regional Monitoring Networks (RMNs) to detect changing baselines in freshwater wadeable streams. (EPA/600/R-15/280). Washington, DC: Office of Research and Development, Washington. Available online at http://www.epa.gov/ncea.

U.S. Environmental Protection Agency. 2020. National Aquatic Resource Surveys. National Rivers and Streams Assessment 2013–2014. Washington, DC: Office of Research and Development, Washington.

Vieira NK, Poff NL, Carlisle DM, Moulton SR, Koski ML, Kondratieff BC (2006) A database of lotic invertebrate traits for North America. US Geological Survey Data Series 187:1-15

Wagner, T., Deweber, J.T., Detar, J. and J.A. Sweka, J.A. 2013. Landscape-scale evaluation of asymmetric interactions between brown trout and brook trout using two-species occupancy models. Transactions of the American Fisheries Society 142:353-361.

Walker, J.D., B.H. Letcher, K.D. Rodgers, C.C. Muhlfeld, and V.S. D’Angelo. 2020. An interactive data visualization framework for exploring geospatial environmental datasets and model predictions. Water 12:2928-2948

Weiskopf, S. R., M. A. Rubenstein, L. G. Crozier, S. Gaichas, R. Griffis, J. E. Halofsky, K. J. W. Hyde, T. L. Morelli, J. T. Morisette, R. C. Muñoz, A. J. Pershing, D. L. Peterson, R. Poudel, M. D. Staudinger, A. E. Sutton-Grier, L. Thompson, J. Vose, J. F. Weltzin, and K. P. Whyte. 2020. Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Science of the Total Environment 733:137782.

Wood, J., P. Bukaveckas, H. Galbraith, M. Gattis, M. Gray, T. Ihde, D. Kreeger, R. Mair, S. McLaughlin, S. Hahn, A. Harvey. 2021. Incorporating Freshwater Mussels into the Chesapeake Bay Restoration Effort. STAC Publication Number 21-004, Edgewater, MD.

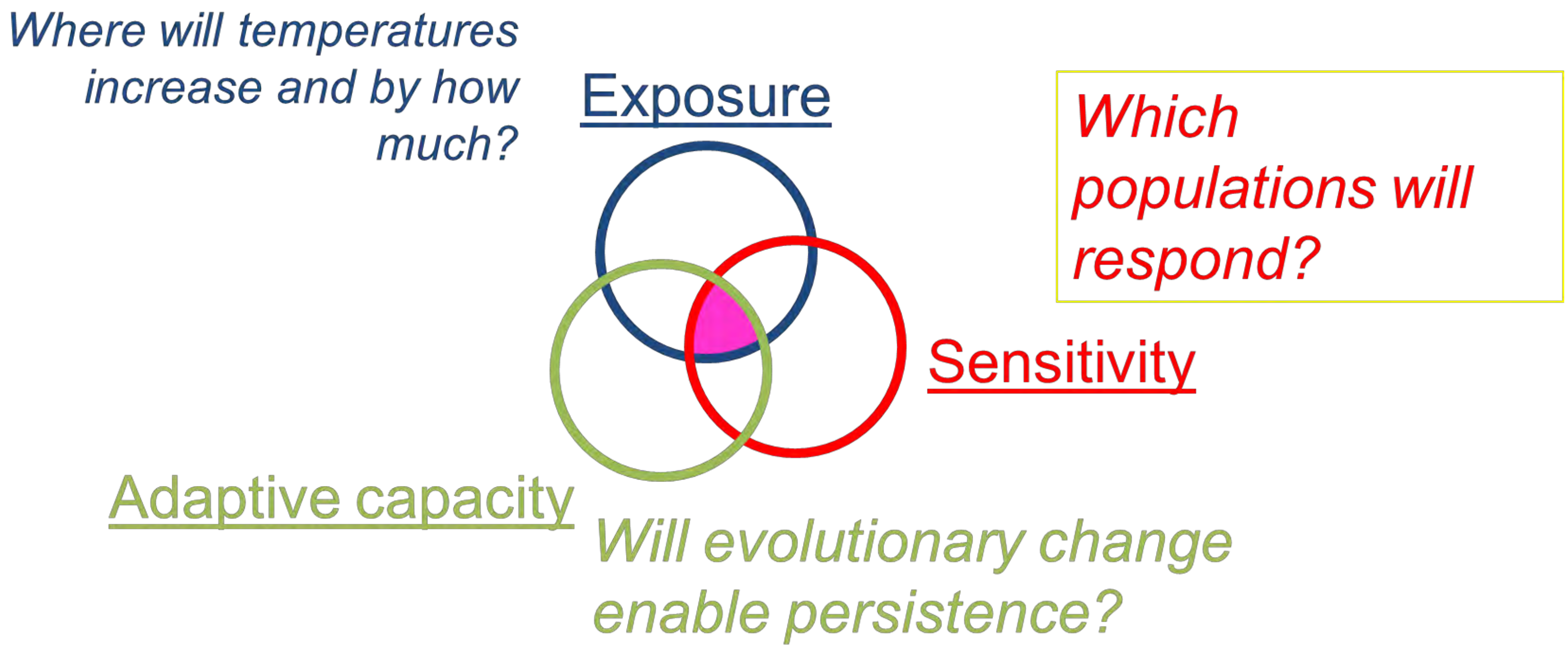


Figure 4. Conceptual model to assess effects of rising water temperatures on aquatic organisms (Adapted from Foden et al. 2013)

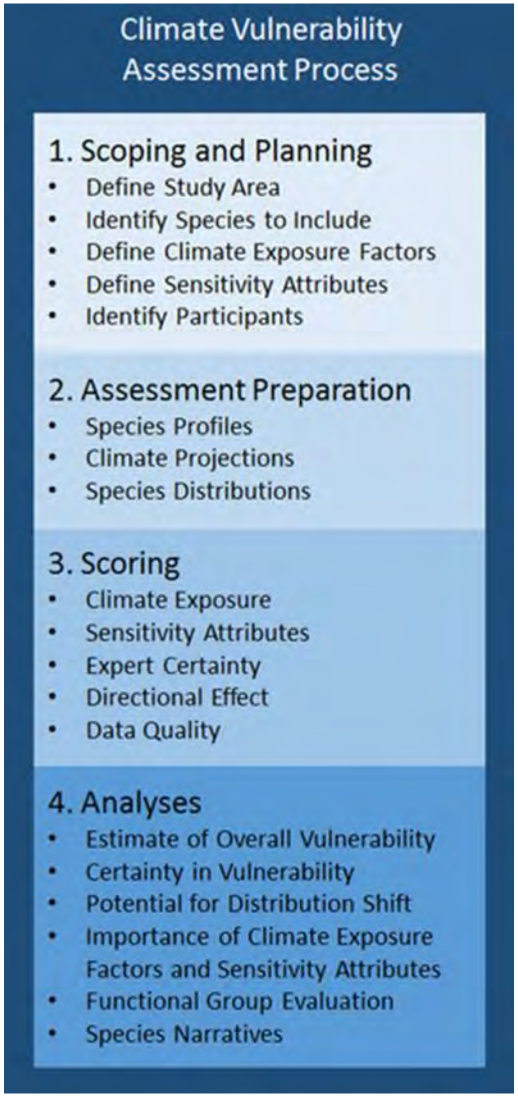


Figure 5. Climate vulnerability assessment process
Source: Hare et al. 2016

Appendix 1. Questionnaire

Request for Information on Stream and River Water Temperatures in the Chesapeake Bay Watershed

Dear Colleague – Water temperature increases have significant ecological implications for the Chesapeake Bay Watershed and could undermine progress toward Chesapeake Bay Program (CBP) Partnership goals for fisheries management, habitat restoration, water quality improvements, and protecting healthy watersheds. There is a critical need for insights into what the CBP Partnership might do now–within the scope of its current goals, policies, and programs–to actively prevent, mitigate or adapt to some of the adverse consequences. A STAC workshop will be held later this year to meet these needs through these primary objectives:

- Summarize major findings on the ecological impacts of rising water temperatures, including science-based linkages between causes and effects; and
- Develop recommendations on how to mitigate these impacts through existing management instruments, ranging from developing indicators, identifying best management practices, and adapting policies.

In preparation for the workshop, we are co-leading the effort to summarize what is already known about where rising stream and river water temperatures will have the most impacts on watershed fish populations and overall stream health. Please respond to the following with any references, links to publications and/or databases, or any other information you think is relevant to this effort by **May 28, 2021** via email ((faulkners@usgs.gov, borsuk.frank@epa.gov). We are not asking for data. Feel free to contact either of us with any questions. Thank you.

1. Information related to temperature sensitivities of key species/groups of species of watershed fish populations cross referenced with the geographical range of their habitats and existing information on where their habitat are most endangered due to increasing water temperatures.

2. Any maps, geospatial data/metadata illustrating these geographic areas.

3. Information related to key stream health indicators and their relative temperature thresholds or sensitivities and existing geographical information on where these specific stream health indicators are most endangered due to increasing water temperatures.

4. Any maps, geospatial data/metadata illustrating these geographic areas.

Thank you.

Stephen Faulkner
U.S. Geological Survey
Eastern Ecological Science Center

Frank Borsuk
U.S. Environmental Protection Agency
Wheeling, WV

Appendix E

Synthesis Element 1 Addendum (Revised): Temperature Water Quality Criteria in CBP Jurisdictions Water Quality Standards and Information on Warmwater Species

ADDENDUM (Revised): Temperature Water Quality Criteria in CBP Jurisdictions' Water Quality Standards and Information on Warmwater Species

A. Contributors

Rebecca Hanmer, EPA-retired; Frank Borsuk, EPA; DC Department of Energy and Environment: Matt Robinson, Hamid Karimi, Steve Saari and Dan Ryan; MD Department of Environment: Jonathan Leiman, Anna Kasko; MD Department of Natural Resources: Daniel Goetz; VA Department of Environmental Quality: Robert Breeding.

B. Resources

The information in this paper was developed through a review of scientific and programmatic information available online from EPA and jurisdiction environmental agencies, and informal solicitation of expert opinion.

C. Approach

We read the Water Quality Standards (WQS) regulations of all Chesapeake Bay Program jurisdictions (available at epa.gov) to determine how they addressed water temperature in water quality criteria, designated fishery uses of water bodies, and policy; pertinent examples were extracted from Maryland, Virginia, Pennsylvania and the District of Columbia for the paper. We also accessed the latest jurisdiction Clean Water Act 305(b) reports available online to see what kinds of temperature-related impairments had been identified. Interviews were then conducted with state agency officials in Maryland, Virginia and the District of Columbia; the paragraphs concerning their activities are based on information they provided. The EPA contributor identified ORSANCO's 2005 compilation of fish research information on temperature endpoints as most pertinent for our use.

D. Synthesis

Synthesis Element 1 emphasizes the effects of rising water temperatures on the species in the Chesapeake Bay watershed's nontidal tributaries which are most sensitive, and therefore vulnerable – that is, coldwater species like brook trout and sculpin, and other aquatic life in cold- and cool-water habitats. As described, jurisdictions in the watershed and scientific agencies are paying close attention to water temperature increases in these habitats.

However, water temperature affects all aquatic species. Thus, temperature rises will affect warmwater species as well. At a certain level, temperature rises will impair species' life stages, and at higher levels, cause lethality. Temperature rises also decrease dissolved oxygen content in water and may affect the habitat of some indigenous fisheries by increasing algal blooms and encouraging invasive species.

All jurisdictions have adopted long-standing legal requirements - Water Quality Standards (WQS) - to protect their fisheries from the effects of heating in the aquatic environment, and these have been approved by U.S. EPA. Established under the Clean Water Act (CWA), the national goal – and the object of the standards -- is to protect beneficial water uses, including a balanced, indigenous population of aquatic life.

Scientific guidance for temperature water quality criteria to protect aquatic species was first published by the federal government in 1968. Despite refinements over the years, today's regulatory WQS follow that framework. The standards all include maximum temperature criteria limits (in degrees C or F), based on "naturally-occurring" temperature regimes. Some standards also explicitly limit the rate and amount of increases above ambient temperature. The standards of every jurisdiction specify the "water uses" for its streams, rivers and lakes. For aquatic life protection, maximum temperature limits are applied for naturally-reproducing "coldwater fisheries" and "warmwater fisheries" – and, where applicable, for waterbodies with stocked fisheries. All criteria are designed to protect the designated uses.

ORSANCO's work on temperature criteria for aquatic life protection contributed to the first federal criteria guidance. ORSANCO's updated 2005 compilation of temperature limits for a number of aquatic species can be viewed by a link in Attachment 1.

Attachment 2 presents the temperature water quality criteria associated with designated water uses for aquatic life protection (fisheries) in the District of Columbia, Maryland, Pennsylvania and Virginia. (The temperature criteria excerpts do not include all the regulatory provisions pertaining to their use, which can be viewed in each jurisdiction's WQS.)

To meet CWA obligations, states are required to monitor their waters to determine whether the designated water uses in their WQS are being protected, and publish a biennial report (CWA 305(b)). They must publish a list under CWA 303(d) every two years of "impaired waters" necessitating follow-up action. Follow-up will generally include more detailed study, and may lead to allocations (limitations) of Total Maximum Daily Load (TMDL) and guidance for measures to restore the established water uses.

When the WQS for temperature were adopted, the focus was to regulate discharges of heated wastewater from thermal power plants and other sources. The possibility that water temperatures would be rising to harmful levels because of climate change is not yet explicitly discussed in the standards. The limited review for this paper found some early instances where Chesapeake Bay watershed jurisdictions have focused on climate-induced water temperature rises that would cause their WQS for aquatic life protection to be exceeded.

- The Maryland Departments of Natural Resources (DNR) and the Environment (MDE) have performed monitoring and modeling related to water temperature rises in naturally-reproducing trout waters. Not only has Maryland's analysis focused on climate-induced water temperature increases, but also on the exacerbating effects of deforestation, agriculture, and impervious runoff from developed areas in the same watersheds.

Maryland has identified numerous thermal impairments in streams with a coldwater fisheries designated use on its 303(d) list of impaired waters (focusing on brook trout). To address these impairments, MDE has been working on developing TMDL methodologies and an implementation guidance for use by local jurisdictions. Maryland hopes to develop its first temperature TMDL and publish the associated implementation guidance sometime in the near future.

Maryland DNR provided a modeling study design for investigating brook trout presence and likelihood of reintroduction success. The work is ongoing, and results are preliminary, but the study shows the kinds of analyses involved to (1) identify key land use, habitat and thermal features associated with brook trout streams; (2) identify the key aquatic insect taxa; and (3) evaluate relationships between air and stream temperature data. Linked here. Maryland also completed a Brook Trout Patch Assessment in 2020, with a full discussion of methods and results. Linked here. Note that other CBP jurisdictions also have brook trout assessment methodologies.

- Virginia has an extensive water temperature monitoring network, and its 2020 305(b) report lists a number of waters – over 100 stream/river segments, lakes and tidal areas – where spot sampling found that temperature water quality criteria were exceeded. Almost all of these segments is a coldwater fishery stream or a managed trout fishery. The Department of Environmental Quality (DEQ) has prioritized 40 sites for investigation of site conditions and a continuous monitoring study. As the current monitoring requirements for WQS attainment and the 305(b) report entail one grab sample at a location, at a random time of the day, there may be stream temperature issues, even with warmwater fisheries, that have not yet been detected.

Thus far, DEQ has done temperature TMDL studies yielding eight allocations, in conjunction with TMDLs for other impairments in the listed waters, but has not yet prepared implementation guidance for temperature impairments.

- The District of Columbia Department of Energy and Environment has implemented several stream restoration projects to improve warmwater aquatic life habitat, especially in National Park areas and the National Arboretum. The most obvious habitat damages to be corrected were extreme bank erosion and pollution associated with flashy urban stormwater runoff, but temperature protection has also been incorporated into the restoration projects.

The District emphasized controlling stormwater runoff first, through "LID" infiltration practices. It cited research showing that biofiltration can reduce stormwater temperature [Jones, Matthew and William F. Hunt, "Effect of Bioretention on Runoff Temperature in Trout Sensitive Regions" presented at 2008 ASCE International Low Impact Development Conference, published online 2012, https://ascelibrary.org/doi; and Paraszcuk, William Dale, "Changes in Stormwater Thermal Loads Due to Bioretention Cells", 2021 Masters Thesis, https://vtechworks.lib.vt.edu.]

The stream restoration design incorporated thermal refugia for aquatic life (e.g. deeper channels where fish could go to cooler water), and preserving/planting riparian trees to shade and cool the stream. Post-project monitoring is showing fish population improvements, such as largemouth bass and sunfish.

The District of Columbia example is illustrative of several things:
– the importance of protecting warmwater fish species and their habitats. These are, after all, the most common species and habitats in the watershed. They are also an important source of fishing for minority and poor communities;
– the need to understand and address the relationship between water temperature rises due to increases in air temperature, and the exacerbating effects of heated stormwater runoff from impervious surfaces;
– the value of cooling stormwater runoff through use of stormwater management practices that infiltrate the runoff; and
– the value of incorporating thermal refugia* and riparian tree protection/shade in stream restoration.
(*A recent U.S. Forest Service white paper, “Climate Change Refugia”/Climate Change Resource Center (usda.gov) discussed “climate change refugia” and defined them as “areas that remain relatively buffered from contemporary climate change over time and enable persistence of valued physical, ecological, and socio-cultural resources.”)

Attachment 1

ORSANCO *Temperature Criteria Re-evaluation,* March 31, 2005. Appendix Table Z-1: Database of temperature endpoints for 125 fish species and 28 macroinvertebrate taxa Linked here.

For information about notable warmwater species, see the following pages: striped bass, white perch, white bass (35-36), largemouth bass (41), smallmouth bass (44-45), bluegill (46-49), pumpkinseed sunfish (49), yellow perch (52).

Attachment 2

WATER QUALITY STANDARDS - TEMPERATURE CRITERIA

All Water Quality Standards (WQS) adopted by the jurisdictions and approved by U.S. EPA are accessible on the web, either through epa.gov or the water quality agency websites. See below the temperature-related provisions contained in the WQS of the three jurisdictions mentioned above: the District of Columbia, Maryland and Virginia. Also here are the temperature provisions of Pennsylvania's WQS, which has a table of maximum temperature limits by time-period. Note that all WQS contain provisions to allow mixing zones, provide for low flow exceptions, and specify stream segments where different criteria may be allowed while still protecting the use. (All excerpts from epa.gov.)

DISTRICT OF COLUMBIA MUNICIPAL REGULATIONS
Chapter 11, Water Quality Standards

1104.5
Class C streams shall be maintained to support aquatic life and shall not be placed in pipes.

1104.8 Unless otherwise stated, the numeric criteria that shall be met to attain and maintain designated uses are as follows (Tables 1 through 3). **Excerpt from Table 1**:

	Temperature (°C)
Maximum	32.2
Maximum change above ambient	2.8

4 At temperatures greater than 29°C, in tidally influenced waters, an instantaneous minimum dissolved oxygen concentration of 4.3 mg/L shall apply.

Annotated Code of MARYLAND
Title 26, Department of the Environment
Subtitle 08 Water Pollution

26.08.02.03-3

.03-3 Water Quality Criteria Specific to Designated Uses.

A. Criteria for Class I Waters -- Water Contact Recreation and Protection of Nontidal Warmwater Aquatic Life.

(3) Temperature.
(a) The maximum temperature outside the mixing zone determined in accordance with Regulation .05 of this chapter or COMAR 26.08.03.03.--.05 may not exceed 90 degrees F (32 degrees C) or the ambient temperature of the surface waters, whichever is greater.
(b) A thermal barrier that adversely affects aquatic life may not be established.
(c) Ambient temperature is the water temperature that is not impacted by a point source discharge.
(d) Ambient temperature shall be measured in areas of the stream representative of typical or average conditions of the stream segment in question.
(e) The Department may determine specific temperature measurement methods, times, and locations.

D. Criteria for Class III Waters — Nontidal Cold Water.
(3) Temperature.
(a) The maximum temperature outside the mixing zone determined in accordance with Regulation .05 of this chapter or COMAR 26.08.03.03—.05 may not exceed 68°F (20°C) or the ambient temperature of the surface waters, whichever is greater.
(b) Ambient temperature — Same as Class I.
(c) A thermal barrier that adversely affects salmonid fish may not be established.
(d) It is the policy of the State that riparian forest buffer adjacent to Class III waters shall be retained whenever possible to maintain the temperatures essential to meeting this criterion.

E. Criteria for Class III-P Waters — Nontidal Cold Water and Public Water Supplies.

(1) Exception. Authorized operation of the Little Seneca Creek Dam means that all operational activities permitted are met under the conditions of a dam operating permit issued by the Department of Natural Resources under Natural Resources Article, §§8-801-8-814, Annotated Code of Maryland, and COMAR 08.05.03. Injury resulting from the authorized operation of Little Seneca Creek Dam to the Class III natural trout fishery recognized in the stream use designation assigned to Little Seneca Creek in Regulation .08 of this chapter is not considered a violation of this chapter.

(2) The following criteria apply:
The criteria for Class HI waters in §D(1)—(7); and....

F. Criteria for Class IV Waters — Recreational Trout Waters.

(3) Temperature.

(a) The maximum temperature outside the mixing zone determined in accordance with Regulation .05 of this chapter or COMAR 26.08.03.03—.05 may not exceed 75°F (23.9°C) or the ambient temperature of the surface waters, whichever is greater.
(b) Ambient temperature — Same as Class I.
(c) A thermal barrier that adversely affects salmonid fish may not be established.
(d) It is the policy of the State that riparian forest buffer adjacent to Class IV waters shall be retained whenever possible to maintain the temperatures essential to meeting this criterion

Code of PENNSYLVANIA

Ch. 93 WATER QUALITY STANDARDS 25 § 93.7

Criteria Critical Use*
Maximum temperatures in the receiving waterbody resulting from heated waste sources regulated under Chapters 92a, 96
and other sources where temperature limits are necessary to protect designated and existing uses.

Temp (°F)	**Cold Water Fisheries**	**Warm Water Fisheries**	**Trout Stocked Fisheries**
January 1-31	38	40	40
February 1-29	38	40	40
March 1-31	42	46	46
April 1-15	48	52	52
April 16-30	52	58	58
May 1-15	54	64	64
May 16-31	58	72	68
June 1-15	60	80	70
June 16-30	64	84	72
July 1-31	66	87	74
August 1-15	66	87	80

August 16-30	66	87	87
September 1-15	64	84	84
September 16-30	60	78	78
October 1-15	54	72	72
October 16-31	50	66	66
November 1-15	46	58	58
November 16-30	42	50	50
December 1-31	40	42	42

Critical Use: The designated or existing use the criteria are designed to protect. More stringent site-specific criteria may be developed to protect other more sensitive, intervening uses.

(b) For naturally reproducing salmonids, protected early life stages include embryonic and larval stages and juvenile forms to 30 days after hatching. The DO standard for naturally reproducing salmonid early life stages applies October 1 through May 31. The DO1 standard for naturally reproducing salmonid early life stages applies unless it can be demonstrated to the
Department's satisfaction, that the following conditions are documented: 1) the absence of young of the year salmonids measuring less than 150 mm in the surface water; and 2) the absence of multiple age classes of salmonids in the surface water. These conditions only apply to salmonids resulting from natural reproduction occurring in the surface waters. Additional biological information may be considered by the Department which evaluates the presence or absence of early life stages.

(c) The list of specific water quality criteria does not include all possible substances that could cause pollution. For substances not listed, the general criterion that these substances may not be inimical or injurious to the existing or designated water uses applies....
(d) If the Department determines that natural quality of a surface water segment is of lower quality than the applicable aquatic life criteria in Table 3 or 5, the natural quality shall constitute the aquatic life criteria for that segment....

9VAC25-260-40. Stream flow.

Man-made alterations in stream flow shall not contravene designated uses including protection of the propagation and growth of aquatic life.

9VAC25-260-50. Numerical criteria for dissolved oxygen, pH, and maximum temperature**.

	DO Min.	EN (mg/I)**** Daily Avg.	pH	Max. Temp. (°C)
Open Ocean	5.0 E-8		6.0-9.0	
Tidal Waters in the Chowan Basin and the Atlantic Ocean Basin	4.0	5.0	6.0-9.0	
Tidal Waters in the Chesapeake Bay and its tidal tributaries	see 9VAC25-260-185		6.0-9.0	
Nontidal Waters (Coastal and Piedmont Zones)	4.0	5.0	6.0-9.0	32
Mountainous Zones Waters	4.0	5.0	6.0-9.0	31
Stockable Trout Waters	5.0	6.0	6.0-9.0	21
Natural Trout Waters	6.0	7.0	6.0-9.0	20

Swamp Waters 3.7-8.0* ** **Maximum temperature will be the same as that for Classes I through VI waters as appropriate. ***The water quality criteria in this section do not apply below the lowest flow averaged (arithmetic mean) over a period of seven consecutive days that can be statistically expected to occur once every 10 climatic years (a climatic year begins April 1 and ends March 31). See 9VAC25-260-310 and 9VAC25-260-380 through 9VAC25-260-540 for site specific adjustments to these criteria.

****For a thermally stratified man-made lake or reservoir in Class III, IV, V or VI waters that are listed in 9VAC25-260-187 these dissolved oxygen and pH criteria apply only to the epilimnion of the waterbody. When these waters are not stratified, the dissolved oxygen and pH criteria apply throughout the water column.

9VAC25-260-60. Rise above natural temperature.

Any rise above natural temperature shall not exceed 3°C except in the case of Class VI waters (natural trout waters), where it shall not exceed 1°C. However, the board can, on a case-by-case basis, impose a more stringent limit on the rise above natural temperature. Natural temperature is defined as that temperature of a body of water (measured as the arithmetic average over one hour) due solely to natural conditions without the influence of any point-source discharge.

9VAC25-260-70. Maximum hourly temperature change.

The maximum hourly temperature change shall not exceed 2°C, except in the case of Class VI waters (natural trout waters) where it shall not exceed 0.5°C. These criteria shall apply beyond the boundaries of mixing zones and are in addition to temperature changes caused by natural conditions.

9VAC25-260-80. Thermal discharges into lakes and impoundments.

In lakes and impoundments receiving thermal discharges, the temperature of the epilimnion, or surface water when there is no stratification, shall not be raised more than 3°C above that which existed before the addition of heat of artificial origin. The board may, on a case-by-case basis, impose a more stringent limit on temperature rise. The increase shall be based on the monthly average of the maximum daily temperature. The temperature of releases from these lakes and impoundments shall be consistent with standards established for the receiving waters. When an applicant for a permit proposes either a discharge of heated effluent into the hypoliinnion or the pumping of water from the hypolimnion for return back into the same body of water, such practice shall not be approved unless a special study shows that the practice will not produce adverse effects.

9VAC25-260-90. Thermal variances.

The temperature limits set forth in 9VAC25-260-50 through 9VAC25-260-80 may be superseded in certain locations where a thermal variance demonstration is performed in accordance with § 316(a) of the Clean Water Act.

B. Basin descriptions. The tables that follow divide the state's surface waters into 10 river basins, some with subbasins: Potomac River Basin (Potomac and Shenandoah Subbasins), James River Basin (Appomattox River Subbasin), Rappahannock River Basin, Roanoke River Basin, Yadkin River Basin, Chowan and Dismal Swamp Basin (Chowan and Albemarle Sound Subbasins), Tennessee and Big Sandy Basins (Big Sandy, Clinch and Holston Subbasins), Chesapeake Bay, Atlantic Ocean and Small Coastal Basin, York River Basin and New River Basin. (See Figure 2.)

Each basin is further divided into sections. Each section is assigned a class, represented by Roman Numerals I through VII, based on its geographic location or, in the case of trout waters, on its use. Descriptions of these classes are found in 9VAC25-260-50.

9VAC25-260-370. Classification column.

> A. DO, pH and temperature criteria. The classification column defines the class of waters to which the basin section belongs in accordance with the class descriptions given in 9VAC25-260-50. 9VAC25-260-50 defines the state's seven classes (I through VTI) and the dissolved oxygen (DO), pH and maximum temperature that apply to each class. By finding the class of waters for a basin section in the classification column and referring to 9VAC25-260-50 the DO, pH and maximum temperature criteria can be found for each basin section.

> B. DGIF trout waters. The Department of Game and Inland Fisheries (DGIF) has established a classification system for trout waters based on aesthetics, productivity, resident fish population and stream structure. Classes i through iv rate wild trout habitat; Classes v through viii rate cold water habitat not suitable for wild trout but adequate for year-round hold-over of stocked trout. The DGIF classification system is included in this publication with the board's trout water classes (Class V— Stockable trout waters and Class VI—Natural trout waters) in the class column of the River Basin Section Tables 9VAC25-260-390 et seq.

DGIF trout water classifications which are not consistent with board classifications for stockable trout waters or natural trout waters are shown with a double asterisk (**) in the class column of the River Basin Section Tables 9VAC25-260-390 et seq. These trout waters have been identified for reevaluation by the DGIF. Those trout waters which have no DGIF classification are shown with a triple asterisk (***). The DGIF classes are described below. Inclusion of these DGIF classes provides additional information about specific streams for permit writers and other interested persons. Trout waters classified as classes i or ii by the DGIF are also recognized in 9VAC25-260-1I 0.

DGIF STREAM CLASS DESCRIPTIONS.
Wild natural trout streams.
Class i. Stream of outstanding natural beauty possessing wilderness or at least remote characteristics, an abundance of large deep pools, and excellent fish cover.
Substrate is variable with an abundance of coarse gravel and rubble. Stream contains a good population of wild trout or has the potential for such. Would be considered an exceptional wild trout stream.
Class ii. Stream contains a good wild trout population or the potential for one but is lacking in aesthetic quality, productivity, and/or in some structural characteristic. Stream maintains good water quality and temperature, maintains at least a fair summer flow, and adjacent land is not extensively developed. Stream would be considered a good wild trout stream and would represent a major portion of Virginia's wild trout waters.
Class iii. Stream which contains a fair population of wild trout with carrying capacity depressed by natural factors or more commonly man-related land use practices. Land use activities may result in heavy siltation of the stream, destruction of banks and fish cover, water quality degradation, increased water temperature, etc. Most streams would be considered to be tube in the active state of degradation or recovery from degradation. Alteration in land use practices would generally improve carrying capacity of the stream.
Class iv. Stream which contains an adequately reproducing wild trout population but has severely reduced summer flow characteristics. Fish are trapped in isolated pools where they are highly susceptible to predators and fishermen. Such streams could quickly be over-exploited and, therefore, provide difficult management problems.
Stockable trout streams.
Class v. Stream does not contain an adequately reproducing wild trout population nor does it have the potential for such. However, water quality is adequate, water temperature is good, and invertebrate productivity is exceptional. Pools are abundant with good size and depth and fish cover is excellent. Stream would be good for stocked trout but may offer more potential for a fingerling stocking program.
Class vi. Stream does not contain a significant number of trout nor a significant population of warmwater gamefish. Water quality is adequate and water temperature good for summer carryover of stocked trout. Summer flow remains fair and adjacent land is not extensively developed. All streams in this class would be considered good trout stocking water.
Class vii. Stream does not contain a significant number of trout nor a significant population of warmwater gamefish. Water quality and temperature are adequate for trout survival, but productivity is marginal as are structural characteristics. Streams in this class could be included in a stocking program but they would be considered marginal and generally would not be recommended for stocking.
Class viii. Stream does not contain a significant number of trout nor a significant population of warmwater gamefish. Water quality and temperature are adequate for trout but summer flows are very poor (less than 30% of channel). Streams in this class can provide good trout fishing during spring and early summer but would not be recommended for summer or fall stocking.
Other. Remaining streams would be considered unsuitable for any type of trout fishery. Streams would be considered unsuitable under any of the following conditions:
- summer temperatures unsuitable for trout survival.
- stream contains a significant population of warmwater gamefish.
- insufficient flow; or
- intolerable water quality.

Appendix F
Synthesis Element 2: Identification of Where Rising Bay Water Temperatures will have the Most Impacts on Bay Fish, Shellfish and Crab Populations and Their Prey Including Identification of Critical Temperatures/Temperature Changes

Synthesis Element 2: Identification of Where Rising Bay Water Temperatures will have the Most Impacts on Bay Fish, Shellfish and Crab Populations and Their Prey Including Identification of Critical Temperatures/Temperature Changes

Abstract

Impacts of rising Chesapeake Bay water temperatures on living resources were explored through the context of five key species chosen on the basis of their economic, ecological, and cultural importance; blue crab, oysters, summer flounder, striped bass, and forage (bay anchovy and menhaden). A review of regional species climate vulnerability scores and bay-specific research, showed a range of positive and negative responses of living resources to temperature and other climate change related factors. Positive impacts are likely for blue crab and some forage species, as warmer temperatures support higher productivity and increased habitat range as species move northward. Negative impacts are predicted for oysters due to their already depressed populations as a result of disease, overfishing and habitat loss. While oysters can thrive in higher temperature regimes and may experience an increase in habitat range, they are highly vulnerable to other climatic impacts such as ocean acidification and changes in salinity driven by precipitation. Striped bass and Summer flounder may experience both negative and positive impacts at different stages of life (larval to adult) and habitat use (rivers and estuaries to marine). The range of responses and potential for localized impacts (for example changes in habitat quality and reproductive success within specific tributaries) leads to higher uncertainty in evaluating Striped bass and Summer flounder vulnerability. The review showed that while rising temperatures are important and do affect species, other climate factors are as if not more important. It also recognizes that rising water temperatures are driven by larger atmospheric air temperature changes and are therefore not likely able to be mitigated through watershed restoration strategies. This suggests existing fishery management approaches will need to adapt by better incorporating climate change impacts into their decision making for currently managed Bay species as well as additional species that are moving north into the bay and increasing in abundance, such as brown shrimp.

A. **Contributors**

Bruce Vogt, NOAA; Mandy Bromilow, NOAA Affiliate; Justin Shapiro, CRC; Jay Lazar, NOAA; Emily Farr, NOAA

B. **Resources**

- NOAA's Northeast Species Climate Vulnerability Ranking Profiles
- NOAA's Habitat Vulnerability Ranking Profiles
- MD Sea Grant Ecosystem-based Fisheries Management Species Fact Sheets
    - Striped Bass
    - Blue Crab

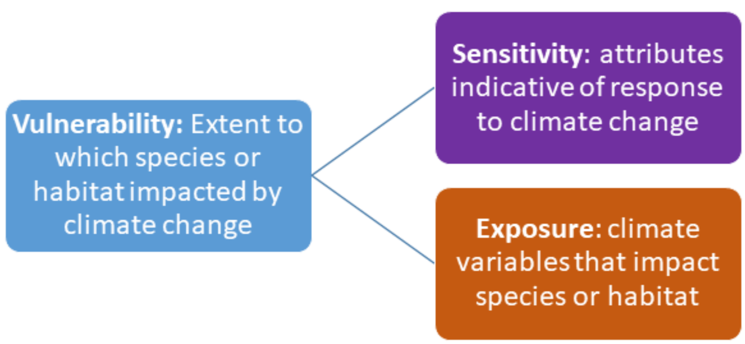
- Other Chesapeake Bay-specific literature put forward by working group members and scientists (Found in bibliography)

C. **Approach**

The synthesis uses representative bay species to contextualize effects from rising temperatures. A number of factors were considered in choosing the representative species. These included, ecological importance, economic value, cultural significance, biological diversity, management structure, and differing anticipated responses to increasing temperatures. These considerations led to synthesis summaries on blue crab, eastern oyster, striped bass, summer flounder, and forage species (bay anchovy, Atlantic menhaden, and polychaetes).

All of the above mentioned species (with the exception of polychaetes) are assigned a climate vulnerability ranking from NOAA's Northeast Fish and Shellfish Climate Vulnerability Assessment (Hare et al. 2016). This assessment ranks species vulnerability by calculating exposure and sensitivity scores using a process of expert elicitation under agreed-upon criteria. Exposure refers to climate variables that impact the species (e.g., rising water temperature), while sensitivity refers to attributes of the species that determine their response to those climate impacts (e.g., occurs in a limited temperature range).

Figure 1. Definitions of Vulnerability, Sensitivity and Exposure used in the assessments



The vulnerability assessment also provides species narratives with a focus on life history, drivers of climate vulnerability, likely climate effects, and predicted distributional shifts. The assessment process can be seen in the flow diagram. Specifics about the vulnerability ranking methodology can be seen here. **An important note on the term "vulnerability": under this assessment vulnerability is the extent to which the abundance or productivity of a**

species may be impacted by climate change, which may be either positive or negative. For example, blue crabs are ranked as very highly vulnerable, but will most likely be a climate change "winner" in the Chesapeake Bay region. Below is a summary of each species, their vulnerability to climate change, sensitivity to increasing temperatures, and impacts on key habitats of interest.

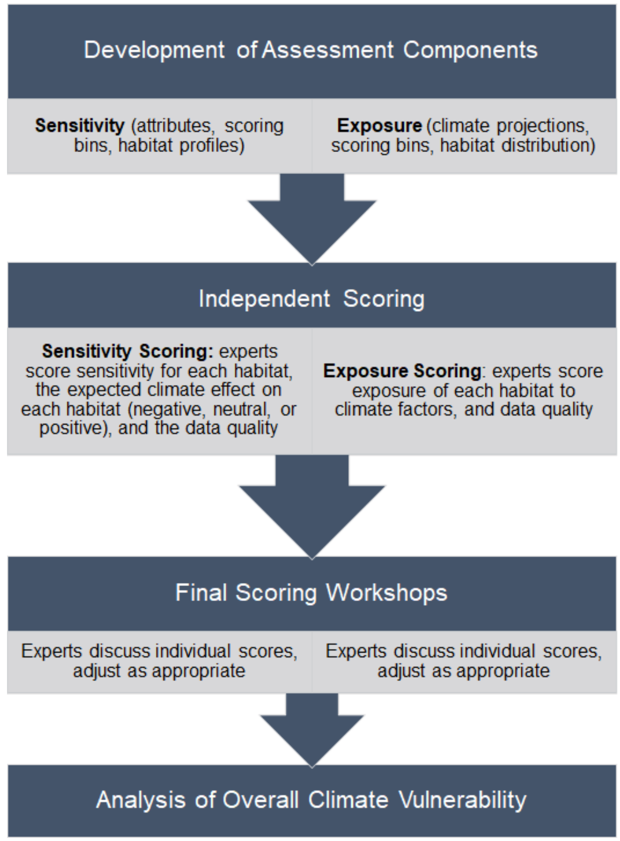


Figure II-2: Process methodology for NOAA's Northeast Climate Vulnerability Rankings

It is important to recognize that temperature is just one of many interconnected stressors that impact species recruitment, health, and abundance. A good example of temperature not telling the full story is the eastern oyster (detailed below). Oysters are classified as "low" for temperature sensitivity according to the NOAA Climate Vulnerability Assessment, as they can be found as far south as the Gulf of Mexico. Other related climatic stressors such as ocean acidification and freshwater input score as "highly sensitive" for oysters, making the species "very highly" vulnerable to a changing climate.

A recently completed NOAA assessment of the climate vulnerability of marine, estuarine, and riverine habitats in the Northeast U.S. using a very similar framework to the one described for fish and shellfish species above (Farr et al. 2021, in prep) was used to consider temperature impacts on key habitats required by the representative species. Estuarine habitats evaluated include salt marsh, SAV, and shellfish reef. Lastly the synthesis provides an overview of existing management frameworks being used to advance climate science priorities and include climate impacts to guide ecosystem based fishery management efforts.

Tasks completed/pursued for this synthesis:

- Compile a table listing temperature sensitivities of key Bay fish, shellfish and crab species/communities and their principal prey cross referenced with the geographical range of their habitats and existing information on where their habitats are most endangered due to increasing water temperatures.
  - Complete
- Describe where observed declines in Bay fish, shellfish and crab can be partially explained by observed increasing water temperatures.

    - We didn't have the resources to answer this on a fine spatial scale. Not completed
- Based on the Partnership's spatial and temporal projections for increasing tidal Bay water temperature in the coming years to decades, lay out the anticipated implications for Bay fish, shellfish and crab species/communities with high sensitivities to water temperatures.
    - Complete
- Share information on the vulnerability, impacts, uncertainty, and science gaps for increasing temperature on key species and habitats using oysters, blue crab, striped bass and bay anchovy as representative species
    - Complete

D. **Synthesis**

Eastern Oyster

Climate Vulnerability: Very High
Temperature Sensitivity: Low

The Eastern Oyster inhabits a wide temperature range from the Gulf of St Lawrence to Venezuela. Given its tolerance for higher temperatures in the southern parts of this range, increasing temperatures in the Bay are not likely to negatively impact oysters. However, other climate factors such as changes in salinity and ocean acidification or lower pH are expected to have negative consequences. Especially since oyster abundances in the Bay are already very low due to overfishing, habitat loss, poor water quality, and disease. Climate change is predicted to increase precipitation in the Chesapeake Bay which could lower salinities and increase run off resulting in more severe hypoxia. Lower salinities can cause mortality of oysters as observed in 2018 and 2019 and create conditions not suitable for reproduction. Higher salinities are associated with higher oyster disease prevalence and greater shell degradation. Ocean acidification (in this case lower pH) makes it more difficult for oysters to create shell and grow. This may lead to the already limited amount of oyster reef habitat to dissolve more quickly or set up a scenario where live oysters cannot grow quickly enough to outpace loss of shell. Current studies are investigating the impacts of ocean acidification further on oyster growth, filtration, reproduction and other functions.

The Chesapeake Bay Program is leading the world in large scale oyster restoration in implementing the outcome to restore 10 tributaries by 2025. Underpinning this approach to restore oysters at a tributary scale is the assessment that these larger scale projects will help oysters be more resilient to changes in the environment. It will be important to consider climate impacts on oysters in future restoration siting, design, reef construction, seeding, hatchery production and monitoring.

Temperature Narrative Information:

- Spawning & Recruitment:
  - Northern climates - spawning occurs in the summer only (EOBRT 2007)
  - Southern climates - spawning can occur all year if temperatures remain above 20 degrees celsius (EOBRT 2007)
  - Reductions in recruitment in Chesapeake Bay were due to decreased spawning stock biomass (decreased spawning stock biomass has also contributed to a decrease in oyster reef substrate needed for recruitment) and climate-driven changes in environmental conditions (Kimmel and Newell, 2007).
- Juveniles:
  - Larvae do not tolerate high temperatures and have a narrower salinity tolerance range than adults (Sellers and Stanley, 1984; EOBRT, 2007).
  - Shell growth of juvenile Eastern Oysters is lower under lower aragonite saturation states (Ries et al., 2009) and lower pH (Waldbusser et al., 2011).
- General:
  - Oyster growth and reproductive rates peak in waters ranging in temperature from 20-30°C and they can live in water temperatures of 0-36°C (Shumway 1996; Lenihan 1999).
  - Though temperature sensitivity for oysters is classified as low, other climatic factors closely connected with temperature, such as ocean acidification and freshwater increases, are driving the species' high vulnerability scores (NOAA Climate Vulnerability Assessment). Warming coupled with eutrophication common in many coastal estuaries will likely amplify the conditions that result in bottom water hypoxia, further contributing to subtidal shellfish reef habitat loss.
  - Exposure to warming (and other stressors) may influence oyster tissue and shell growth later in the oyster's life. Responses to current stress can be strongly shaped by previous stress exposure, and may influence the fitness, production, and restoration. (Donelan et al. 2021)
  - Warming air and water can increase the susceptibility of shellfish to disease, parasites and predation by local and invasive species (Smolowitz 2013; Burge et al. 2014).

Likely Distributional Shift/Impact from Climate:

- The effect of climate change on Eastern Oyster on the Northeast U.S. Shelf is very likely to be negative (>95% certainty in expert scores).

Blue Crab

Climate Vulnerability: Very High
Temperature Sensitivity: Moderate

Temperature Narrative Information:

- Spawning & Recruitment:
  - Female blue crabs may mature and mate earlier because of warming temperatures. However small size at maturation increases vulnerability to predation and diminishes the number of offspring produced per brood. (MD Sea Grant EBFM)
- Juvenile:
  - Predation and cannibalism on juveniles is also higher during warm seasons; therefore the juvenile portion of the population might also be negatively impacted by the extended warm temperatures predicted. (MD Sea Grant EBFM)
- General:
  - Blue Crab survival in Chesapeake Bay is higher during mild winters (Rome et al., 2005; Bauer and Miller, 2010), meaning warmer winters should lead to higher survival and population productivity.
  - Blue Crab also are moving into the Gulf of Maine and this has been linked to increasing temperatures (Johnson, 2014).

Likely Distributional Shift/Impact from Climate:

- The effect of climate change on Blue Crab on the Northeast U.S. Shelf is estimated to be neutral, but with a moderate degree of uncertainty (66-90% certainty in expert scores).
- Warming may lead to increased productivity and northward shifts in the region, both of which would represent positive effects of climate change, but more research is needed to confirm these effects.

Striped Bass

Climate Vulnerability: Very High
Temperature Sensitivity: Low/Moderate

Temperature Narrative Information:

- Spawning & Recruitment:
  - Temperature induced overwinter mortality of juveniles is important for recruitment in northern portions of striped bass range. (Hurst and Conover, 1998)
  - Survival of striped bass larvae is highest at temperatures of 18 degrees celsius. (Secour and Houde, 1995). Continued Bay warming will likely result in a fast transition of spring to summer, reducing optimal temperature time for larval survival (MD Sea Grant EBFM).
- General:

- Increasing summer temperatures resulted in a reduction of Chesapeake Bay striped bass habitat. (Coutant and Benson 1990)
- Winter warming could also promote year-round residency, and reduce overwinter juvenile mortality leading to increased pressure on the forage species targeted by striped bass. (MD Sea Grant EBFM)
- Earlier migrations, during warmer springs, can increase chances of spawning/recruitment prior to set catch seasons hence lowering fish mortality prior to reproduction. (Peer and Miller 2014)
- As found by Coutant and Cox, striped bass' thermal niches in mature specimens are most optimal between 24 and 26 degrees (Uphoff, 2011)
- Striped bass detections indicated tolerance of a wide range of surface water temperatures, including those >25°C, which regional regulatory bodies stipulate are stressful for this species. Still, during summer and fall striped bass selected the lowest-available temperature and avoided water temperature >27°C, demonstrating that Chesapeake Bay striped bass can encounter habitat compressions due to the behavioural avoidance of bottom hypoxia and high temperatures. (Itakura et al. 2021)

Likely Distributional Shift/Impact from Climate:

- The effect of climate change on Striped Bass on the Northeast U.S. Shelf is estimated to be neutral, but with a moderate degree of uncertainty (66-90% certainty in expert scores). The uncertainty likely stems from the complex life history and the potential for different aspects of climate change to affect the species differently.
- Increasing temperatures could reduce habitat in the southern part of the Northeast U.S. Shelf while increasing habitat in the northern portions.

<u>Summer Flounder</u>

Climate Vulnerability: Moderate
Temperature Sensitivity: Low

Temperature Information Narrative:

- Summer Flounder productivity may change with the changing climate. Recent changes in Summer Flounder distribution also have been identified and linked to climate (Pinsky et al 2013)
- Other evidence suggests that changes in Summer Flounder distribution are linked to reductions in fishing and expanding population rather than changes in temperature. (Bell et al, 2014; Murawski, 1993)

Likely Distributional Shift/Impact from Climate:

- The effect of climate change on Summer Flounder on the Northeast U.S. Shelf is estimated to be neutral but with high uncertainty (<66% certainty in expert scores).
- Adult distribution has shifted northward, but this is linked to changes in fishing.
- Also, productivity of the stock has remained fairly constant over the past 3 decades, during which temperatures in the ecosystem have increased.

<u>Forage (Anchovy, Menhaden, Polychaetes)</u>

Climate Vulnerability: Low to Moderate
Temperature Sensitivity: Low

Temperature Information Narrative:
- There have been surprisingly few studies of the effect of climate change on Anchoa spp., especially in the Northeast U.S. Shelf ecosystem.
  - A bioenergetics model was developed for anchovies in the Chesapeake Bay; work indicated that bay anchovy consumption of zooplankton will increase with warming waters. (Lou and Brandt, 1993)
  - A Black Sea ecosystem bioenergetics model was also developed, indicating population productivity of anchovies would increase as temperature increases. (Güraslan et al., 2014)
- The rate of springtime warming, i.e. how quickly water temperatures rise in the spring, is a primary driver of forage fish abundance. Faster (earlier) springtime warming leads to decreased abundance of forage fishes. (Woodland et. al, 2021)

Likely Distributional Shift/Impact from Climate:
- The effect of climate change on anchovies on the Northeast U.S. Shelf is very likely to be positive (>95% certainty in expert scores). As warming continues more habitat in the Northeast U.S. is expected to become available.
- Based on research in other regions, population productivity is also likely to increase with continued warming.
- The effect of climate change on Atlantic Menhaden on the Northeast U.S. Shelf is very likely to be positive (90-95% certainty in expert scores). Recruitment will likely increase as temperature warm and more spawning occurs in the region. Adult distribution will likely extend northwards and the species may re-occupy the Gulf of Maine during summertime.

<u>Shifting species distributions</u>
- There is evidence that climate drivers including temperature are allowing range expansion for cobia, brown shrimp, and red drum. The impacts of southern species moving into the Bay are not fully understood. However, the increased abundance of

brown shrimp has led to a new fishery in the Bay and some scientists have pointed to red drum increasing predation pressure on species such as blue crab.

Invasive Species

- There were no vulnerability assessments conducted specific to invasive species in the Chesapeake Bay. Here we classify invasive species as those introduced to non-native habitats from factors other than northward climate-driven distribution shifts. A number of key invasive generalists (ie. Blue Catfish) are increasing in abundance, impacting trophic interactions, and driving attention to management response. Typically, these generalists are classified as climate change “winners” with less restrictive temperature/salinity ranges than many native bay specialists. More on invasive catfish is available in the 2017 Invasive Catfish Symposium Workshop Summary.
- The Northeast habitat climate vulnerability assessment included invasive wetlands, which were determined to be moderately vulnerable to climate change. Invasive wetlands were the only habitats in the assessment expected to be positively impacted by climate change, given their high adaptation to disturbance and the likelihood that invasive wetland plants will outcompete native salt marsh species.

Vulnerable Habitats Important to Representative Bay Species

Changing temperature impacts these species in both direct and indirect ways. Importantly, eastern oyster, blue crab, striped bass, and forage species all rely on nearshore habitats that are highly or very highly vulnerable to climate change. The impact of rising temperatures on these habitats will therefore have implications for the species that depend on those habitats. The table below details the habitat dependence of each of these species by life stage on a few key estuarine habitats: salt marsh, SAV, and shellfish reef. The impacts of rising temperature on water column habitat is described in the text below, but not included in the table, since each of the representative species depends on the water column throughout its life cycle. The importance of each habitat by life stage comes from a habitat-species matrix developed by the Atlantic Coastal Fish Habitat Partnership (ACFHP). The habitat climate vulnerability rankings come from Farr et al. 2021, and the species vulnerability rankings from Hare et al. 2016.

Habitat Name	Species	Importance of habitat by life stage (ACFHP)			
		Eggs/Larva	Juvenile/YOY	Adult	Spawning Adult
Estuarine emergent wetland	Striped bass		Moderate	Moderate	
	Blue crab		High	High	
	Summer flounder		High	Moderate	
	Winter flounder	High	Moderate		High

Estuarine submerged aquatic vegetation	Striped bass		Moderate	Moderate	
	Black sea bass		High		
	Blue crab	Very high	Very high		
	Summer flounder		High	Moderate	
Estuarine shellfish reef	Black sea bass		High	High	
	Blue crab	Moderate	Moderate	Moderate	
	Summer flounder		Moderate		
	Menhaden			Low	
Legend		*Very High Vulnerability*	*High Vulnerability*	*Moderate Vulnerability*	*Low Vulnerability*

Climate Vulnerability and Impacts of Rising Temperature on Key Habitats

Estuarine Emergent Wetland:

Very highly vulnerable to climate change

- Most salt marsh flora are eurythermal. Rising temperatures may lead to changes in plant physiological processes including an increase in photosynthetic rates and plant biomass (Charles and Dukes 2009; Gedan and Bertness 2010; Kirwan and Mudd 2012).
- Temperature can have indirect effects on salt marshes by influencing production of soil organic matter, rates of evaporation and decomposition, and salt marsh community composition (Najjar et al. 2000; Charles and Dukes 2009; Gedan and Bertness 2009; Gedan and Bertness 2010; Carey et al. 2017). Salt marshes are also sensitive to changes in the marsh platform, as rising temperatures can cause an increase in decay rate of organic matter. This may offset the enhanced productivity and soil carbon accumulation associated with increased temperatures (Kirwan and Blum 2011).
- The precise responses of coastal wetlands to increased warming are difficult to predict given the complexity of interactions among biological and environmental factors (Cahoon et al. 2009). For example, Kirwan et al. (2009) reported an increase in productivity of smooth cordgrass throughout its range in North America by about 50-100 g per m^2 per year under a projected warming of 2-4°C. For the Mid-Atlantic and New England regions, this would represent a 10-40% increase in productivity for smooth cordgrass, which approximates the projected marsh losses due to sea level rise.

Estuarine Submerged Aquatic Vegetation:

Highly vulnerable to climate change

- Increases in water temperature may impact the normal timing of flowering and seed production in both eelgrass and widgeon grass (Short and Neckles 1999). Increases in water temperature as small as 1°C have been shown to advance flower formation in eelgrass by 12 days and seedling maturation by 10.8 days (Blok et al. 2018). It is not clear what changes in the timing of the normal reproductive cycle may mean for the long term survival of individual meadows.

- Increased water temperatures may lead to a reduction in the distribution and productivity of eelgrass over its existing range (Moore et al. 1996; Short and Neckles 1999). Widgeon grass is unlikely to be negatively affected by increasing water temperature along the Atlantic coast due to its higher temperature tolerance (Kantrud 1991). As water temperatures increase, widgeon grass distribution is likely to increase in the study area, replacing eelgrass meadows in the southern portion of eelgrass' current distribution (Moore et al. 2014). For most of its range, eelgrass actively grows from spring through fall. At the southern edge of its range, eelgrass grows from fall through spring, disappearing in the summer (Thayer et al. 1984; Short and Neckles 1999). As sea surface temperature increases, it is likely this adaptation in the growing season will move northward (Short and Neckles 1999).
- Increased water temperature may also lead to greater survival and distribution of invasive species that negatively impact eelgrass (Neckles 2015; Carman et al 2019; Young and Elliot 2020). Warmer winter temperatures have led to greater green crab overwinter survival (Young and Elliott 2020), which have been shown to cause the decline of hundreds of acres of eelgrass in Maine and Canada (Neckles 2015). Invasive tunicates also have the potential to lead to eelgrass shoot mortality (Wong and Vercaemer 2012). Latitudinal changes in invasive tunicates distribution on eelgrass have been documented, and changing water temperature is likely contributing to this shift (Carman et al. 2016; Carman et al. 2019).
- Meadows with higher genetic diversity have proven more resilient to extended heat waves (Dubois et al. 2019).

<u>Estuarine Shellfish Reef</u>

Very highly vulnerable to climate change
See above section on Eastern Oyster climate vulnerability

<u>Estuarine Water Column</u>

Highly vulnerable to climate change

- Water temperature in estuaries is largely influenced by heat exchange with the atmosphere and freshwater input, the temperature of which is also influenced by heat exchange with the atmosphere (Hare et al. 2010). The temperature of the region's estuaries have warmed over the past several decades (Bell et al. 2014).
- Stratification in estuaries is unlikely to change much because of wind and tidal mixing. However, stratification could increase as a result of increased freshwater inflows and increased air temperatures (Najjar et al. 2010). Changes in stratification could have consequences for oxygen-levels; hypoxia does occur in estuarine systems throughout the Northeast largely as a result of summertime thermal stratification and increased primary production (Nixon et al. 2009)

Science Gaps:

- There is a need for downscaled climate models with better resolution in the nearshore and coastal environments for projected temperature and other factors.
- Both the species and habitat climate vulnerability assessments described here were conducted at a regional scale. Climate change often impacts species and habitats at much smaller scales, with variability between estuaries, watersheds, or basins. Finer-scale assessments of climate vulnerability may be something to work towards.
- Spatial information on the distribution of habitats is fairly limited for several habitat types, highlighting a need for better data.

E. **Evaluation**

Key Findings

- Species-specific vulnerability reports highlight differential impacts of rising water temperatures and other climate change impacts in Chesapeake Bay.
  - Blue crab, menhaden, bay anchovy are likely to experience positive impacts as increasing temperatures expand habitat range and productivity.
  - Oysters are likely to experience negative impacts due largely to climate change factors other than temperature.
  - Striped bass and Summer flounder may experience both negative and positive impacts at different life stages (larval to adult). Localized impacts on spawning timing and/or nursery habitats caused by temperature could drive changes in populations at a coast wide scale. There is uncertainty about the overall trajectory of impact.
- Northward shifts in species range are being documented for several species. This is resulting in some Bay species shifting populations north while other species from the south are becoming more prevalent in the Bay. These range shifts can result in changes to species abundance and distributions, food web dynamics, fishing behavior and new fisheries. Likewise habitats required by fish and shellfish species are shifting in range and experiencing impacts that lead to changes in fish abundance, distribution and reproduction success.
- Better information on and integration of species and habitat specific impacts within the Chesapeake Bay are needed to track changes and inform management strategies.

Management Implications

- Mitigation of rising water temperatures is not a likely option. Therefore fishery management approaches will require better information on species and habitat impacts to help incorporate climate change into existing management structures. The ongoing shift to ecosystem based fishery management is laying the groundwork for this type of information to be utilized in a management context. It is important to note that some species such as blue crabs and oysters are managed by Bay jurisdictions, some such as Striped bass, Summer flounder and Menhaden are managed by regional bodies and some such as bay anchovy are not managed at all. This suggests different approaches and decision makers will need to be considered in evaluating any new climate change management scenarios.

- Oyster reefs are a key habitat type that could be significantly impacted by climate change. Future restoration will likely need to consider climate impacts on oyster project siting, design, reef construction, seeding, hatchery production and monitoring.
- Warming winter temperatures may impact the methods by which blue crab populations are assessed and the current management framework.
- Species range shifts will require management frameworks as new fisheries emerge and existing fisheries are modified.

Next steps

Climate impacts on fisheries threaten fishing communities, the economy, and require new science based approaches to managing fishery resources. The NOAA Fisheries Climate Science Strategy is part of a proactive approach to increase the production, delivery, and use of climate-related information needed to support management. The Strategy identifies seven objectives which will provide decision-makers with the information they need to reduce impacts and increase resilience with changing climate and ocean conditions.

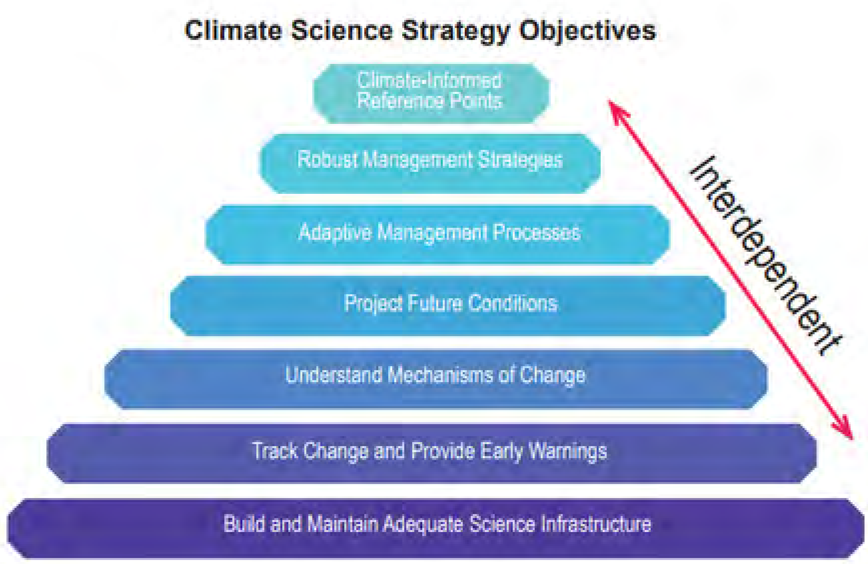


Figure II-3: Climate Strategy Objectives from NOAA Fisheries Climate Science Strategy

- The Strategy responds to growing demands for information and tools to prepare for and respond to climate impacts on marine and coastal resources. It is being implemented through **Regional Action Plans** that focus on building regional capacity, partners, products and services to address the seven objectives.
- The NOAA Chesapeake Bay Office has prioritized impacts of changing environmental conditions including climate change in recent research funding opportunities. NCBO is collaborating with scientists funded through those opportunities to develop habitat suitability models and indicators that link temperature and other climate factors to impacts on striped bass, summer flounder and forage fish. The results of these studies can help inform Bay Program and regional fishery management decisions.
- NOAA publishes an annual State of the Ecosystem Report for the Mid Atlantic. This report includes a section on habitat risks, climate and species implications. The report is used by the Mid Atlantic Fishery Management Council to update their Ecosystem Approach to Fisheries Management Risk Assessment. This is an example of how climate information can be synthesized for use by managers.

The Fisheries GIT, NOAA, USGS and others are sponsoring critical research on the impacts of changing environmental conditions of fishery resources and habitats. The Fish GIT will track findings from this emerging science and convene partners to discuss applications of this work for indicator development and management. Some of the projects under way or recently completed include:

- Seasonal summaries tracking changes in temperature and salinity using NOAA observations with a narrative on likely impacts to blue crab, striped bass, oysters, summer flounder, forage and their habitat.
- Estuarine Habitat Condition Index for Summer flounder (Gartland, VIMS)
- Forage Habitat Suitability Models (Mary Fabrizio, VIMS)
  - Suitable habitat for anchovy was classified as bottom average of 23.7-27 degrees celsius
  - Increased temperature is expected to increase suitability for anchovy (and other high tolerance forage) but it's unclear the interaction with other climate change factors like lowered salinity
- Suitability of Striped Bass Nursery Habitat (Rachel Dixon, VIMS)
- Leveraging multi-species and multi-year telemetry datasets to identify seasonal, ontogenetic, and interannual shifts in habitat use and phenology of Chesapeake Bay fishes (Furey, UNH; Ogburn, SERC)
- Striped bass and summer flounder abundance trends and influencing factors in the Chesapeake Bay: an ecosystem-based evaluation (Jiao, VT)
- SST Heat Wave Forecasts for the Chesapeake Bay (Andrew Ross NOAA)

F. **Bibliography**

References Cited

Bauer LJ, Miller TJ. Spatial and interannual variability in winter mortality of the blue crab (Callinectes sapidus) in the Chesapeake Bay. Estuar Coasts. 2010; 33(3): 678-687. DOI: 10.1007/s12237-009-9237-x

Bell, R. J., Hare, J. A., Manderson, J. P., & Richardson, D. E. 2014. Externally driven changes in the abundance of summer and winter flounder. ICES Journal of Marine Science 71(9):2416-428.

Bell RJ, Richardson DE, Hare JA, Lynch PD, Fratantoni PS. Disentangling the effects of climate, abundance, and size on the distribution of marine fish: an example based on four stocks from the Northeast US shelf. ICES J Mar Sci. 2014; fsu217. doi: 10.1093/icesjms/fsu217

Blok SE, Olesen B, Krause-Jensen D. 2018. Life history events of eelgrass Zostera marina L. populations across a gradient of latitude and temperature. Marine Ecology Progress Series 590:70-93. https://doi.org/10.3354/meps12479.

Burge CA, Eakin CM, Friedman CS, Froelich B, Hershberger PK, Hofmann EE, Petes LE, Prager KC, Weil E, Willis BL, Ford SE, Harvell CD. 2014. Climate change influences on marine infectious diseases: implications for management and society. Annual Review of Marine Science 6:249-77.

Cahoon DR, Reed DJ, Kolker AS, Brinson MM, Stevenson JC, Riggs S, Christian R, Reyes E,Voss C, Kunz D. 2009. Coastal wetland sustainability. Coastal sensitivity to sea-level rise: a focus on the Mid-Atlantic Region. [Titus JG, Anderson KE, Cahoon DR, Gesch DB, Gill SK, Gutierrez BT, Thieler ER, Williams SJ (eds)]. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Synthesis and Assessment Product 4.1. 57-72.

Carey JC, Moran SB, Kelly RP, Kolker AS, Fulweiler RW. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts 40(3):626-39.

Carman MR, Colarusso PD, Nelson EP, Grunden DW, Wong MC, McKenzie C, Matheson K, Davidson J, Fox S, Neckles HA, Bayley H, Schott S, Dijkstra JA, Stewart-Clark S. 2016. Distribution and diversity of tunicates utilizing eelgrass as substrate in the western North Atlantic between 39o and 470 north latitude (New Jersey to Newfoundland). Management of Biological Invasions 7(1):51-7.

Carman MR, Colarusso PD, Neckles HA, Bologna P, Caines S, Davidson JDP, Evans, NT, Fox SE, Grunden DW, Hoffman S, Ma KCK, Matheson K, McKenzie CH, Nelson EP, Plaisted H, Reddington E, Schott S, Wong MC. 2019. Biogeographical patterns of tunicates utilizing eelgrass as a substrate in the western North Atlantic between 39o and 47o north latitude (New Jersey to Newfoundland). Management of Biological Invasions 10(4):602-16.

Charles H, Dukes JS. 2009. Effects of warming and altered precipitation on plant and nutrient dynamics of a New England salt marsh. Ecological Applications 19(7):1758-73.

Coutant CC, Benson DL. Summer habitat suitability for striped bass in Chesapeake Bay: reflections on a population decline. Trans Am Fish Soc. 1990; 119(4): 757-778. doi: 10.1577/1548- 8659(1990)119<0757:SHSFSB>2.3.CO;2

Donelan, S. C., Breitburg, D., and Ogburn, M. B.. 2021. Context-dependent carryover effects of hypoxia and warming in a coastal ecosystem engineer. Ecological Applications 31(4):e02315. 10.1002/eap.2315

Eastern Oyster Biological Review Team (EOBRT). Status review of the eastern oyster (Crassostrea virginica). Report to the National Marine Fisheries Service, Northeast Regional Office. 2007. NOAA Tech. Memo. NMFS F/SPO-88, 105 p. Available:
http://www.nmfs.noaa.gov/pr/species/Status%20Reviews/eastern_oyster_sr_2007.pdf

Farr ER, Johnson MR, Nelson MW, Hare JA, Morrison WE, Lettrich MD, Vogt B, Meaney C, Howson UA, Auster PJ, Borsuk FA, Brady DC, Cashman MJ, Colarusso P, Grabowski JH, Hawkes JP, Mercaldo-Allen R, Packer DB, Stevenson DK. 2021. An assessment of marine, estuarine, and riverine habitat vulnerability to climate change in the Northeast U.S. PloS One (in prep).

Gedan KB, Bertness MD. 2009. Experimental warming causes rapid loss of plant diversity in New England salt marshes. Ecology Letters 12(8):842-8.

Gedan KB, Bertness MD. 2010. How will warming affect the salt marsh foundation species Spartina patens and its ecological role? Oecologia 164(2):479-87.

Güraslan C, Fach BA, Oguz T. Modeling the impact of climate variability on Black Sea anchovy recruitment and production. Fish Oceanogr. 2014; 23(5): 436-457. doi: 10.1111/fog.12080

Hare JA, Alexander MA, Fogarty MJ, Williams EH, Scott JD. 2010. Forecasting the dynamics of a coastal fishery species using a coupled climate–population model. Ecological Applications 20(2):452-64.

Hare JA, Morrison WE, Nelson MW, Stachura MM, Teeters EJ, Griffis RB, et al. A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental Shelf. PLoS One. 2016; 11(2):e0146756. doi: 10.1371/journal.pone.0146756.

Hikaru Itakura, Michael H P O'Brien, David Secor, Tracking oxy-thermal habitat compression encountered by Chesapeake Bay striped bass through acoustic telemetry, ICES Journal of Marine Science, 2021;, fsab009, https://doi.org/10.1093/icesjms/fsab009

Hurst TP, Conover DO. Winter mortality of young-of-the-year Hudson River striped bass (Morone saxatilis): size-dependent patterns and effects on recruitment. Can J Fish Aquat Sci. 1998; 55(5): 1122- 1130. doi: 10.1139/cjfas-55-5-1122

Johnson DS. The savory swimmer swims north: a northern range extension of the blue crab Callinectes sapidus?. J Crust Biol. 2015; 35(1): 105-110. DOI: 10.1163/1937240X-00002293

Kantrud HA. 1991. Widgeongrass (Ruppia maritima L.): a literature review. U.S. Fish and Wildlife Service. Fish and Wildlife Research 10. 58 pp.

Kimmel DG, Newell RI. The influence of climate variation on eastern oyster (Crassostrea virginica) juvenile abundance in Chesapeake Bay. Limnol Oceanogr. 2007; 52(3): 959-965. doi: 10.4319/lo.2007.52.3.0959

Kimmel DG, Tarnowski M, Newell RI. Long-term (1939 to 2008) spatial patterns in juvenile eastern oyster (Crassostrea virginica, Gmelin 1791) abundance in the Maryland portion of Chesapeake Bay. J Shell Res. 2012; 31(4), 1023-1031. doi: http://dx.doi.org/10.2983/035.031.0414

Kirwan ML, Blum LK. 2011. Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. Biogeosciences 8(4):987-93.

Kirwan ML, Guntenspergen GR, Morris JT. 2009. Latitudinal trends in Spartina alterniflora productivity and the response of coastal marshes to global change. Global Change Biology 15(8):1982-9.

Kirwan ML, Mudd SM. 2012. Response of salt-marsh carbon accumulation to climate change. Nature 489(7417):550-3.

Lenihan HS. 1999. Physical-biological coupling on oyster reefs: how habitat structure influences individual performance. Ecological Monographs 69:251-75.

Lou J, Brandt SB. Bay anchovy production and consumption in mid-Chesapeake Bay based upon a bioenergetics model and acoustic measurements of fish abundance. Mar Ecol Prog Ser. 1993; 98: 223- 236.

Marsh JA, Dennison WC, Alberte RS. 1986. Effects of temperature on photosynthesis and respiration in eelgrass (Zostera marina L.). Journal of Experimental Marine Biology and Ecology 101:257-67.

Moore KA, Neckles HA, Orth RJ. 1996. Zostera marina (eelgrass) growth and survival along a gradient of nutrients and turbidity in the lower Chesapeake Bay. Marine Ecology Progress Series 142(1-3):247-59.

Murawski SA. Climate change and marine fish distributions: forecasting from historical analogy. Trans Am Fish Soc. 1993; 122(5): 647-658. doi: 10.1577/1548-8659(1993)122<0647:CCAMFD>2.3.CO;2

Najjar RG, Pyke CR, Adams MB, Breitburg D, Hershner C, Kemp M, Howarth R, Mulholland MR, Paolisso M, Secor D, Sellner K, Wardrop D, Wood R. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine, Coastal and Shelf Science 86(1):1-20.

Najjar RG, Walker HA, Anderson PJ, Barron EJ, Bord RJ, Gibson JR, Kennedy VS, Knight CG,Megonigal JP, O'Connor RE, Polsky CD, Psuty NP, Richards BA, Sorenson LG, Steele EM, Swanson RS. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. Climate Research 14(3):219-33.

Neckles HA. 2015. Loss of eelgrass in Casco Bay, Maine, linked to green crab disturbance. Northeastern Naturalist 22(3):478-500.

Nixon, S. W., Fulweiler, R. W., Buckley, B. A., Granger, S. L., Nowicki, B. L., & Henry, K. M. 2009. The impact of changing climate on phenology, productivity, and benthic–pelagic coupling in Narragansett Bay. Estuarine, Coastal and Shelf Science 82(1):1-18.

Peer, A. & Miller, Thomas. (2014). Climate Change, Migration Phenology, and Fisheries Management Interact with Unanticipated Consequences. North American Journal of Fisheries Management. 34. 10.1080/02755947.2013.847877.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., & Levin, S. A. (2013). Marine taxa track local climate velocities. Science, 341, 1239–1242. https://doi.org/10.1126/science.1239352

Ries JB, Cohen AL, McCorkle DC. Marine calcifiers exhibit mixed responses to CO2-induced ocean acidification. Geol. 2009; 37(12), 1131-1134. doi: 10.1130/G30210A.1

Rome MS, Young-Williams AC, Davis GR, Hines AH. Linking temperature and salinity tolerance to winter mortality of Chesapeake Bay blue crabs (Callinectes sapidus). J Exp Mar Biol Ecol. 2005; 319(1): 129-145. DOI: 10.1016/j.jembe.2004.06.014

Secor, D.H., Houde, E.D. Temperature effects on the timing of striped bass egg production, larval viability, and recruitment potential in the Patuxent River (Chesapeake Bay). Estuaries 18, 527–544 (1995). https://doi.org/10.2307/1352370

Sellers MA, Stanley JG. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic) – American oyster. 1984. U.S. Fish Wildl. Serv. FWS/OBS-82/11.23. U.S. Army Corps of Engineers, TR EL-82-4. 15 pp. Available: http://www.nwrc.usgs.gov/publications/specprof.htm

Short FT, Neckles HA. 1999. The effects of global climate change on seagrasses. Aquatic Botany 63:169-96.

Shumway CA. 1999. A neglected science: applying behavior to aquatic conservation. Environmental Biology of Fishes 55:183-201.

Smolowitz R. 2013. A review of current state of knowledge concerning Perkinsus marinus effects on Crassostrea virginica (Gmelin) (the Eastern oyster). Veterinary Pathology 50(3):404-11.

Thayer GW, Kenworthy WJ, Fonseca MS. 1984. The ecology of eelgrass meadows of the Atlantic coast: a community profile. U.S. Fish Wildlife Service. FWS/OBS-84/02. 147pp.

Waldbusser GG, Voigt EP, Bergschneider H, Green MA, Newell RI. Biocalcification in the eastern oyster (Crassostrea virginica) in relation to long-term trends in Chesapeake Bay pH. Estuar Coasts. 2011; 34(2): 221-231. 10.1007/s12237-010-9307-0

Wong MC, Vercaemer, B. 2012. Effects of invasive tunicates and a native sponge on the growth, survival, and light attenuation of eelgrass (Zostera marina). Aquatic invasions 7(3):315-26.

Woodland, R.J., Buchheister, A., Latour, R.J. et al. Environmental Drivers of Forage Fishes and Benthic Invertebrates at Multiple Spatial Scales in a Large Temperate Estuary. Estuaries and Coasts 44, 921–938 (2021). https://doi.org/10.1007/s12237-020-00835-9

Young AM, Elliott JA. 2020. Life history and population dynamics of green crabs (Carcinus maenas). Fishes 5(1):4. https://doi10:3390/fishes5010004.

Appendix G
Synthesis Element 3: Submerged Aquatic Vegetation (SAV)

Synthesis Element 3: Submerged Aquatic Vegetation (SAV)

A. CONTRIBUTORS/Element Team

Brooke Landry, CBP SAV Workgroup Chair
Becky Golden, CBP SAV Workgroup Vice-Chair
Marc Hensel, Virginia Institute of Marine Science
Chris Patrick, Virginia Institute of Marine Science
Dick Zimmerman, Old Dominion University
Rhianne Cofer, Old Dominion University
Bob Murphy, TetraTech

Special acknowledgements are offered to the authors of *Chesapeake Bay SAV: A Third Technical Synthesis*: Tom Arnold, Dick Zimmerman, Katia Engelhardt, and Court Stevenson. Parts of the TS III chapter on SAV and Climate Change were copied verbatim into this document.

AT A GLANCE SUMMARY

· The three primary symptoms of climate change that will directly affect Chesapeake Bay SAV: rising water temperatures, increased CO_2 concentrations, and sea level rise.

· Temperature impacts to eelgrass are well understood. Without drastic improvements in water clarity or a reversal of warming trends, viable populations of eelgrass will likely be extirpated from Chesapeake Bay. The Bay's most economically significant fishery – blue crabs (*Callinectus sapidus*) – is directly dependent on eelgrass.

· Temperature impacts to other Chesapeake Bay SAV species are not as well studied but appear to be less dramatic than those to eelgrass. Increasing temperatures negatively impact all Chesapeake Bay SAV communities to some extent.

· The CO_2 fertilization effect may counterbalance some of the impacts from warming, but unknowns associated with invasive species, pathogens, cyanobacteria, etc. may set that balance awry.

· Management efforts (ie. the Chesapeake Bay TMDL) that have reduced N and P in the Chesapeake have facilitated recovery of SAV, and SAV are more resilient to all climate stressors if water clarity is maximized. The single most effective action to protect Chesapeake Bay SAV is to sustain and accelerate improvements in water quality and clarity through N, P, and TSS load reductions.

· The currently funded climate and SAV modeling project will be instrumental in answering many questions.

· SAV restoration efforts for diverse species may mitigate some of the loss of SAV from areas unable to recover without a seed source.

B. RESOURCES

Chesapeake Bay Submerged Aquatic Vegetation (SAV): A Third Technical Synthesis: This technical synthesis (TS III) for Chesapeake Bay SAV was a multi-institutional effort to synthesize the state of the science completed in December 2016 and includes a detailed chapter on the known effects of climate change, including increasing temperatures. The chapter on climate is called *21st Century Climate Change and Submerged Aquatic Vegetation in the Chesapeake Bay*, and was written by Tom Arnold, Dick Zimmerman, Katia Engelhardt, and Court Stevenson. Because information about temperature impacts to Chesapeake Bay SAV was already synthesized in TS III, much of the information was copied directly into the synthesis below for ease of translation.

Virginia Institute of Marine Science (VIMS) Bay-wide Aerial Survey data This dataset provides annual information on the distribution and density of SAV throughout the Chesapeake Bay and its tributaries for all years since 1984 and allows for analysis of SAV trends in relation to water quality, clarity, and climate change related stressors, including increasing temperatures.

VIMS Ground-truthing observations and transect data: VIMS has collected ad-hoc SAV data from reliable sources since the beginning of the survey. Data collection has been sporadic and non-standardized, but the data collected has contributed to our understanding of the distribution of various species of SAV throughout the Bay. VIMS also conducts SAV surveys at long-term permanent transects. These transects are used to confirm SAV density and bed edge delineated in the aerial survey, and are standardized and reliable.

Chesapeake Bay SAV Watcher data: Though only recently developed and implemented, the SAV Watcher program data collected by Riverkeepers and watershed groups throughout the Bay have been helpful in identifying restoration sites and donor beds, and will be invaluable in the coming years for tracking climate impacts to specific species.

Chesapeake Bay SAV Sentinel Site Program: This nascent program is still in the development stage, but was initially conceptualized in order to track the impacts of climate change on SAV at a more detailed scale than either the Bay-wide aerial survey or the CB SAV Watcher program can provide. Though collection of data at "new" sites will begin in 2022, several existing long-term transects will be adopted as sentinel sites, so historical data will be available in some areas.

Chesapeake Bay SAV Fact Sheets: The Chesapeake Bay SAV Synthesis Project brought together experts from the CBP partnership specializing in SAV, water quality, and land-use research and management. The goal of the project was to conduct a synthesis of multiple long-term datasets to determine what role the growing human population in the Chesapeake Bay watershed has played in influencing SAV distribution and abundance and if the sustained efforts and management actions implemented by the CBP partnership have benefited SAV habitat. Additionally, the SAV Synthesis Project team conducted segment-specific reviews of SAV trends and progress towards restoration targets and created SAV fact-sheets for each segment. This local-scale segment review of SAV in each tributary aims to provide a summary of information that may guide local planning and implementation of best management practices (BMPs) to encourage SAV recovery throughout the Bay. Although information from the fact sheets was not specifically referenced in the chapter following, they are mentioned here because SAV loss is often attributed to heat events, and these events are discussed in many of the fact sheets.

Published Papers: See Bibliography

C. APPROACH

No new analyses were conducted solely for the purposes of this chapter. Rather, the authors pulled heavily from the recently synthesized information in the TS III chapter on climate and SAV as well as on more recently published research. Additionally, authors included information regarding currently funded, on-going, and Chesapeake Bay-specific studies to learn more about rising temperature impacts on SAV. Preliminary results are included where available.

D. SYNTHESIS

INTRODUCTION

Submerged aquatic vegetation (SAV) in Chesapeake Bay and globally provides vitally important ecosystem services. These include the provision of food, habitat, refuge, and nursery grounds for commercially, recreationally, and ecologically important fish, shellfish, and a variety of invertebrates. Even waterfowl use SAV beds extensively. The submerged plants also take in and process excess CO_2 and nutrients, which helps mitigate impacts from climate change by sequestering carbon and decreasing the opportunity for macroalgae and phytoplankton blooms, including harmful algal blooms (HABS), by removing their fuel source. As they take up CO_2 and release O_2, SAV beds buffer the impacts of coastal acidification on the vulnerably shelled organism either living within the beds or nearby. Their physical presence in the water column baffles current and wave energy, reducing shoreline erosion.

Because of its importance, the Chesapeake Bay Program (CBP) and its partners have committed to achieving and sustaining 185,000 acres of SAV in Chesapeake Bay. This 185,000-acre target is the cumulative sum of 92 individual segment targets which state and local governments are attempting to achieve primarily by improving water quality and clarity conditions. In 2010, the Chesapeake Bay Total Maximum Daily Load (TMDL) was implemented. This "pollution diet" had the effect that two and a half decades of insufficient regulatory policies did not. Between 1984, when an annual Bay-wide aerial SAV survey was initiated and 2010 when the TMDL was implemented, SAV acreage went from just under 40,000 acres to just under 80,000 acres, essentially doubling. That represents slow but steady progress but was not impactful enough to entertain the idea of reaching the ultimate or interim SAV restoration targets (2017: 90,000 acres; 2025: 130,000 acres) on time or possibly ever. Between 2010 and 2018, however, following implementation of the TMDL, SAV expanded from 80,000 acres to 108,000 acres, showing that significant management actions and consequent improvements in water quality can in fact facilitate the recovery of the Bay's SAV (Lefcheck et al., 2018).

Unfortunately, it has become apparent that current efforts to reduce nutrient and sediment loads to the Bay may be insufficient to ensure the long-term sustainability of SAV recovery in Chesapeake Bay. In 2020, just over 62,000 acres of SAV were mapped in the Bay, representing a loss of more than a third of the Bay's grasses in a two-year time frame. The loss was largely a result of rapidly degraded water quality from increased precipitation and the consequent run-off and elevated nutrient and sediment loads entering the Bay, broad fluctuations in salinity, and elevated water temperatures. Increased and more intense periods of precipitation are predicted symptoms of climate change which will inflate the current long-term reductions in water clarity and regional decreases in salinity observed in the Bay. These symptoms as well as others, such as rising water temperatures, will likely impact our ability to meet our SAV restoration targets and the impacts will vary among the Bay's salinity regimes and SAV communities.

WHAT WE KNOW ABOUT TEMPERATURE EFFECTS ON CHESAPEAKE BAY SAV

In 2016, members of the Chesapeake Bay Program's SAV Workgroup completed *Chesapeake Bay Submerged Aquatic Vegetation: A Third Technical Synthesis (TS III*) (Landry et al. 2016). The synthesis, conveniently for this purpose, includes a chapter on "21st Century Climate Change and SAV in Chesapeake Bay." The authors (Arnold, Zimmerman, Engelhardt, and Stevenson) scoured, evaluated, and synthesized the available literature to determine what impacts, if any, climate change and its associated stressors will have on the various SAV communities and species in the Chesapeake. Explained in more detail below, Arnold et al. found both reasons for concern and hope. The "CO_2 fertilization effect" caused by increased atmospheric CO_2 concentrations may counterbalance some of the known detrimental stressors that SAV will face, including rising water temperatures. On the other hand, a litany of unknowns may set that balance awry.

The following text is largely copied directly from TS III. Bracketed [text] indicates that this chapter's authors have added text for clarification or updated information and citations that were published after TS III was completed and either support or refute Arnold et al.
In short, Arnold et al. concluded "that [SAV] restoration efforts will be complicated by new stressors associated with accelerating climate change. In the Chesapeake Bay these are: a mean temperature increase of 2-6°C, a 50-160% increase in CO_2 concentrations, and sea-level rise of 0.7-1.6m. Warming alone has the potential to eliminate eelgrass (*Zostera marina)*, the once dominant seagrass, from the Chesapeake. Already high summer temperatures cause mass die-offs of this cool-water species, which lives near its thermal limits [in the Chesapeake]. During this century, warming will continue and the Chesapeake will begin to exhibit characteristics of a subtropical estuary, with summer heat waves

becoming more severe. This will favor native heat-tolerant species such as widgeon grass (*Ruppia maritima*) and certain ecotypes of freshwater SAV, and may facilitate colonization by subtropical seagrasses. Intensifying human activities will also fuel biological processes, such as eutrophication, that drive coastal zone acidification. The resulting high CO_2 / low pH conditions, shaped by diurnal, tidal, and seasonal cycles, may benefit SAV. The *"CO_2 fertilization effect"* has the potential to stimulate photosynthesis and growth in at least some species of SAV and this may offset the effects of thermal stress, facilitating the continued survival of eelgrass at some locations. This equipoise between two forces - thermal stress and acidification - may ultimately determine the fate of cool-water plants in warming estuaries such as the Chesapeake Bay. Finally, sea level rise will reshape the shorelines of estuaries, especially the Chesapeake Bay where land subsidence is significant. Where waters are permitted to migrate landward, suitable habitat may persist; however, where shorelines are hardened SAV may be lost. Our understanding of SAV responses to these three stressors have greatly improved in recent years and allow us to make basic, testable predictions regarding the future of SAV in estuaries. The indirect effects of climate change on associated organisms, however, including fouling organisms, grazers, and microbes, are poorly understood. These indirect effects are likely to prevent smooth transitions, triggering abrupt phase changes in estuarine and freshwater SAV communities subjected to a changing climate."

Regarding temperature impacts, specifically, "Chesapeake Bay waters are predicted to warm by 2 to 6° C, on average, during this century. This is similar to global forecasts for surface air temperatures and ocean surface temperatures, which are predicted to increase 1.1 to 6.4° C and 3 to 4 ° C, respectively (Levitus et al. 2001; Meehl et al. 2007; Intergovernmental Panel on Climate Change [IPCC] 2007, 2014, 2021). These increases in temperature would be in addition to the 0.8 °C increase in mean global surface temperatures that has already occurred, as a result of atmospheric CO_2 exceeding 400 ppm. There are direct, first-order relationships between atmospheric carbon dioxide levels, air temperatures, and Chesapeake Bay water temperatures (Wood et al. 2002). In some areas of the Bay, such as the main stem of the Bay and the Potomac estuary, water temperatures are increasing faster than air temperatures (Ding and Elmore 2015). Unless there is a drastic change in the prevailing "business-as-usual" scenario whereby CO_2 levels continue to rise, exceeding 1000 ppm in the atmosphere over the next century, observed warming of Chesapeake Bay waters will continue in the future. In this case the Chesapeake Bay is likely to develop characteristics of a subtropical estuary by the next century.

Although average temperature projections represent a useful window into climate change, they provide an incomplete picture of the thermal environment, particularly in the near-term when the most devastating temperature effects may result from an increase in the frequency, duration, and amplitude of periodic summer heat waves (IPCC 2014). Furthermore, warming of the Chesapeake Bay will not occur uniformly. Local water temperatures will continue to depend upon circulation patterns that affect ocean mixing, precipitation, and other factors, all of which are impacted by climate change. The greatest and most inconsistent warming will almost certainly occur in shallow waters, the habitats of submerged vegetation, as well as in areas affected by urbanization, such as the Patapsco

River in Baltimore (Ding and Elmore 2015).

For Chesapeake Bay SAV, which can live close to their thermal limits, even moderate warming is problematic (Somero 2002; Hughes et al. 2003). Most Bay species are considered to be "temperate" species, with an optimal growth temperature of 11.5° C to 26° C. In general, increasing temperatures alter rates of photosynthesis and respiration, interfere with life-cycles, trigger disease outbreaks and algal blooms, and cause increased seagrass mortality e.g., (Campbell et al. 2006). The ability of SAV to tolerate warming will however be species-specific (McMahon 2005; Campbell et al. 2006; Walker et al. 2006).

Eelgrass. [Although the CO_2 fertilization effect may counter the negative impact of climate warming on eelgrass growth (Zimmerman et al. 2017), light intensities must be sufficient for photosynthesis to take advantage of the more abundant CO_2 substrate (Zimmerman 2021). Consequently,] general consensus supports the prediction that increased temperatures will adversely impact eelgrass populations in Chesapeake Bay during this century (Najjar et al. 2010). *Zostera marina* is a temperate species with an optimal water temperature of approximately 10-20° C, with 16-17° C being an optimal range for seedling growth (Niu et al. 2012). Colder temperatures are tolerated and plants remain healthy at 5° C. At these colder temperatures growth is slowed (Nejrup and Pedersen, 2008) but photosynthesis:respiration ratios are maximized (Marsh et al. 1986; Zimmerman et al. 1989). Eelgrass growth rates increase linearly from 5 to 25° C (Kaldy 2014). Beyond this temperature, however, deleterious effects emerge. High temperatures of 25-30° C depress rates of photosynthesis and growth (Zimmerman et al. 1989; Niu et al. 2012) and dramatically increase mortality. Marsh et al. (1986) determined that above 30°C, *Zostera marina* has a negative net carbon balance, photosynthesis becomes overwhelmed by increasing rates of respiration, and plants decline rapidly. [Hammer et al. (2018) found that high temperatures (30°C) negatively affect eelgrass growth, tissue integrity, nitrogen metabolism and protein/enzyme synthesis.] The impact of elevated temperatures can be worse in low light. Kaldy (2014) showed the temperature-induced increase in eelgrass respiration can be problematic even at temperatures between 10-20° C when light is limiting photosynthesis (also see Ewers 2013; Jarvis et al. 2014). In theory, eelgrass could escape deleterious temperatures by retreating to deeper, cooler waters (McKee et al. 2002; York et al. 2013). Increasing colonization depth, however, is not likely to be a successful strategy for adapting to future climate change, as the lower depth of eelgrass is restricted by light penetration and climate change is likely to cause further deterioration of water clarity in the Chesapeake (Thayer et al. 1984; McKee et al. 2002; York et al. 2013). The poor tolerance of elevated temperatures suggests a bleak future for eelgrass in the Chesapeake Bay.

The impacts of thermal stress have already been observed in the Chesapeake and neighboring coastal bays in Delaware, Maryland and Virginia. Extended warm periods, such as those occurring in the 1980s and 1990s, have been linked to population declines of eelgrass in the eastern Atlantic (Glmarec 1997). Acute warming from summertime heat waves has triggered shoot mortality and population declines. Eelgrass diebacks in the Goodwin Islands and York River Chesapeake Bay National Estuarine Research Reserve in

Virginia during 2005 were attributed to a greater frequency and duration of water temperatures above 30°C (Moore and Jarvis 2008; Moore et al. 2014). These authors noted a tipping point at 23° C; changing eelgrass cover from 2004 to 2011 was linked with temperatures below and above 23° C, respectively. Although a variety of other factors influence the thermal tolerance of *Z. marina*, it is clear that temperatures above 25°C or, more generally, increases of 1-5°C above normal summertime temperatures, can trigger large-scale die-off of eelgrass in the Chesapeake Bay (Jarvis et al. 2012; Moore et al. 2012, 2014; Jarvis et al. 2014). For example, these authors predicted that: (1) short-term exposures to summer temperatures 4-5° C above normal will "result in widespread diebacks that may lead to *Z. marina* extirpation from historically vegetated areas, with the potential replacement by other species" (Moore et al. 2014); (2) longer-term average temperature increases of 1-4° C are predicted to "severely reduce or eliminate" *Zostera marina* from the Chesapeake Bay (Moore et al. 2012, 2014); and "an increase in the frequency of days when summer water temperature exceeds 30°C will cause more frequent summer die-offs" and is likely to trigger a phase change from which "recovery is not possible" (Carr et al. 2012).

Similar losses have been predicted in neighboring regions, e.g. for the Bogue Sound-Back Sound in North Carolina (Micheli et al., 2008). Restored eelgrass meadows are also vulnerable as higher temperatures (at or above 30° C) are associated with summer die-offs and failures of these new meadows (Tanner et al. 2010; Carr et al. 2012). Similarly, successful SAV restoration in the neighboring coastal bays has been attributed to cooler temperatures (Orth et al. 2010, 2012; Moore et al. 2012) and more favorable water quality resulting in a better light environment (Zimmerman et al. 2015).

Widgeongrass. *Ruppia maritima* tolerates a wider range of temperature and salinity conditions than does eelgrass (Stevenson 1988). It ranges along the eastern coastline of North America from Florida to Nova Scotia and is distributed within meso- and polyhaline portions of the Chesapeake Bay, though populations are patchy and ephemeral (Stevenson et al. 1993). Although biomass does not approach that of eelgrass in the lower polyhaline region of the Bay, it can be the dominant SAV species in the meso- and polyhaline regions of the central Bay, even in intertidal flats when temperatures are moderate in spring and fall (Staver et al. 1996). Unlike eelgrass, *Ruppia* tolerates a wide range of water temperatures ranging from 7 to 40° C. Ideal growth conditions have been reported to range from 20 to 25° C or even 18 to 30° (see Pulich 1985; Lazzar and Dawes 1991; Moore et al. 2014). Anderson (1969) sampled SAV from a thermal plume at the Chalk Point Power Plant on the Patuxent River and found that the lethal temperature was 45°C. Although *Ruppia* tolerates these conditions, higher temperatures have a negative influence on photosynthesis beyond 25°C. For instance, Evans et al. (1986) observed that the maximum photosynthetic rate (P_{max}) increased with temperatures up to 23°C before becoming inhibited (compared to 19°C for *Z. marina* in the same study).

Ruppia sp. reproduction is also impacted by temperature. Optimal seed germination occurs at 15-20°C. In Europe, seed germination was observed to occur at temperatures beginning at 16°C but only after a period of cold stratification at 2-4°C (Van Vierson et al. 1984). If the Chesapeake becomes more subtropical, it may eventually not be cold enough for presently adapted *Ruppia* plants to reproduce by seed, reducing overall population resilience. Temperature changes may have other subtle effects on future population cycles; for example, plants germinated at low temperatures reproduce much more quickly than plants germinated at higher temperatures.

Ruppia's very wide temperature tolerance may make it a "winner" in a warmer climate, replacing eelgrass in much of the lower Bay. This has already been observed [in several locations (Stevenson et al. 1993), including the York River (Moore et al., 2014; Shields et al. 2018, 2019), when unusually high summer temperatures caused die-offs of eelgrass which facilitated a shift from eelgrass to widgeon grass. Outside of the Chesapeake], *Zostera*-to-*Ruppia* transitions occurred in San Diego Bay following the 1997-8 El Niño Southern Oscillation (ENSO), leading Johnson et al. (2003) to predict that a warming of 1.5 to 2.5° C would result in *"a permanent shift in the local seagrass vegetation from eelgrass to widgeongrass"* in this bay.

Freshwater species. Lower salinity regions of the Chesapeake and its tributaries are also experiencing significant warming (Seekell and Pace 2011; Ding and Elmore 2015; Rice and Jastram 2015). Warming may decrease photosynthesis and increase respiration (Ryan 1991), thereby impacting the distribution, modes of reproduction, germination, growth, and dormancy of freshwater SAV (Welch 1952; Barko and Smart 1981; Lacoul and Freedman 2006).

The response of freshwater aquatic plants to climate warming is often species-specific, and may vary even for locally-adapted "biotypes" of a single species (Haller et al. 1976; Haag and Gorham 1977; Madsen and Adams 1988; Barko and Smart 1981; Pip 1989; Svensson and Wigren-Svensson 1992; Spencer and Ksander 1992; Santamaria and Van Vierssen 1997; Rooney and Kalff 2000; Sala et al. 2000; Lacoul and Freedman 2006; Amano et al. 2012). Some species exhibit earlier germination and increased productivity, while others do not (McKee et al. 2002; Lacoul and Freedman 2006). Most submerged freshwater plants require temperatures above 10°C during the growing season, exhibit optimal growth between 10° and 20° C, but do not survive temperatures above 45°C (Anderson 1969; Lacoul and Freedman 2006).

Myriophyllum spicatum, a non-native species, also has a broad temperature range with optimal photosynthesis between 30 to 35°C (Barko and Smart 1981; Nichols and Shaw 1986). Similarly, net photosynthesis of *Potamogeton crispus*, another non-native species, is also highest around 30° C (Nichols and Shaw 1986). *Stuckenia pectinata* prefers 23 to 30° C for early growth (Spencer 1986) and can tolerate 35° C (Anderson 1969). [Wittyngham et al. (2019) found that higher temperatures tended to have positive effects on *S. pectinata* traits and that high salinity treatments had few negative effects except when temperature was coolest. This could explain the recent migration of *S. pectinata* in the Bay from oligohaline to mesohaline waters. As the Bay warms, it is moving into higher saline environments.] Perhaps the most temperate sensitive species that occurs in freshwater areas of the Bay is *Elodea canadensis* with a reported range of 27 to 35° C (Santamaria and van Vierssen 1997; Olesen and Madsen 2000). In complementary growth chamber experiments, *Elodea canadensis* from the Chesapeake Bay performed best at 28°C but were stressed at higher temperatures that are commonly experienced in the thermal plume (32°C) of C. P. Crane Power Station (Beser 2007). However, populations of the same species may vary widely in their adaptation to warm temperatures. For example, *Vallisneria americana*, the most dominant freshwater SAV species in the Chesapeake Bay, is reported to grow best between 33 and 36° C (Korschgen and Green 1988). However, Beser (2007) observed that *Vallisneria* from the Chesapeake Bay were able to survive 36°C over a six-week period whereas plants from Wisconsin could not, suggesting that conspecific plants are acclimated or are adapted to different temperatures through phenotypic plasticity and genetic diversity.

Warming may also impact the reproduction of freshwater SAV. Germination for many species requires cold stratification. However, warmer conditions and an extended growing season, now increasing at a rate of over 1 day per year (Kari Plough et al. in prep.), cause species such as *Potamogeton* spp., *Stuckenia pectinata* and *Vallisneria americana* to germinate more quickly, grow deeper, become more productive, and yield more biomass (Hay et al. 2008; Jarvis and Moore 2008; Yin et al. 2013; Bartleson et al. 2014). Cao et al. (2014) observed that temperature also increases growth of periphyton on aquatic macrophytes (an effect that was dependent upon the presence or absence of periphyton grazers). Periphyton overgrowth is a major problem for the survival of *Potamogeton perfoliatus* in the upper portion of Chesapeake Bay where grazers are not effective in cleaning leaves, leading to a decline of light availability (Kemp et al. 1983; Staver 1984).

Unlike marine seagrass beds that are often monotypic, freshwater beds often consist of a diversity of SAV species (Crow 1993) with different niche requirements. These differences provide some insurance against changes in the environment - as one species declines due to unfavorable conditions, another may compensate and increase in abundance. Thus, it has been suggested that increasing temperatures may have neutral effects on communities or even enhance species diversity within temperate freshwater aquatic plant communities (Grace and Tilley 1976; Haag 1983; Rooney and Kalff 2000; Heino 2002; Lacoul and Freedman 2006). However, warming may eventually compromise and weaken diversity. For example, observations of the SAV community within and outside the thermal effluent of the power generating station C. P. Crane located along Dundee and Saltpeter Creeks of the Gunpowder River, MD, (Beser 2007) show that SAV cover and diversity are both generally lower inside the thermal plume and that temperature is an important environmental gradient. SAV diversity is also impacted when warming boosts the productivity of non-native species such as *Hydrilla verticillata*, which colonized the tidal freshwater regions of the Chesapeake Bay from further south in the 1980s. This species possesses a variety of physiological adaptations that allow it to thrive in conditions that exclude native species (e.g. *Vallisneria americana*) in freshwater (Haller and Sutton 1975; Staver and Stevenson 1995).

It is worth noting that freshwater SAV habitats have been among the most highly-altered ecosystems, altered by human activity and non-native species, motivating new insights and approaches to resource management in the 21st century. Restoring freshwater SAV communities to *"an earlier condition or stable state"* is often no longer possible (Moyle 2014). This realization spawned the new field of "reconciliation ecology", described by Rosenzweig

(2003) as the *"science of inventing, establishing, and maintaining new habitats to conserve species diversity in places where people live, work, and play"* and by Moyle (2014) as *"a practical approach to living with the new reality"* where resource managers take *"an active approach to guiding ecosystem change to favor desired species"* (see Hershner and Havens, 2008). Within the context of climate change, our poor understanding of how warming impacts freshwater SAV limits this type of "active management". To manage the impacts of climate warming on freshwater aquatic plants, we require not only a better understanding of thermal tolerance of dominant plant species, but also their interactions with grazers and microbiota, which can be symbiotic or pathogenic (e.g. fungi, bacteria, archaea, viruses, phages and etc.)

Comparison to other regions. Thermal stress impacts seagrasses inhibiting other coastal ecosystems beyond the Chesapeake. For example, it is well-established that changing climate conditions have impacted populations of *Posidonia oceanica* in the Mediterranean (between 1967 and 1992; Marba and Duarte 1997). More recently, Olsen et al. (2012) documented reduced growth rates, leaf formation rates and leaf biomass per shoot in response to warming from 25-32°C on *Posidonia oceanica* and *Cymodocea nodosa* from the Mediterranean Sea. Climate-induced thermal stress is a concern for Australian seagrasses as well, where *Zostera muelleri* was deemed *"sensitive to temperatures predicted under future climate change scenarios"* (York et al. 2013). *Z. muelleri* from southeast Australia has a thermal tolerance similar to *Z. marina* in the Chesapeake: it "grows optimally at 27° C, shows signs of thermal stress at 30°C, and exhibits shoot mortality at 32° C" (York et al. 2013). A modest warming of 2° C is believed to be responsible for a loss of *Z. muelleri* and a transition to the smaller, more tolerant *Halophila ovalis*, a shift that has persisted at one site for 33 years. Thomson et al. (2015) reported the >90% die-back of the temperate seagrass, *Amphibolis antarctica*, in Shark Bay, Australia, following an extreme heat event in 2010-11. These, and other studies, strongly suggest that climate warming could lead to the local extinction of seagrasses with low thermal tolerance in regions beyond the Chesapeake (Short and Neckles 1999).

Complication Factors. Climate warming will alter the diversity, composition, and functioning of SAV, grazers, fouling organisms, and pathogens (Blake and Duffy 2010; Blake et al. 2012). Some of the community-level changes that are likely to be triggered by warming include: increased eutrophication and poorer light penetration; proliferation of epiphytes that grow on the leaves of SAV; increases in harmful sediment sulfide levels (Goodman et al. 1995; Garcia et al. 2013); and increases in outbreaks of the seagrass wasting disease caused by the microbial pathogen *Labyrinthula* spp. (Kaldy 2014, but see Olsen and Duarte 2015 and Olsen et al. 2015). These interacting forces are likely to trigger episodic events, pass ecological thresholds, trigger tipping points, and induce phase changes so as to make it more difficult to predict the future of SAV communities. Wood et al. (2002) surmised that *"While it is likely that a prolonged warming will lead to a shift in the ecosystem favoring subtropical species over temperature species, physical or ecological factors other than temperature may preclude a smooth transition to a balanced <subtropical> ecosystem."*

Conclusion. Logically, nutrients and light have received the majority of attention for influencing SAV growth rates and survival in the Chesapeake Bay. However, long-term observations and research have also shown that temperature is an important environmental factor that controls the germination, growth, reproduction and mortality of SAV. These effects will become even more important in the future with global climate change and the continued development and urbanization of coastal zones. The direct impacts of warming on most marine seagrasses are relatively well-understood. An abundance of evidence suggests that the outlook is poor for eelgrass (*Z. marina*), a cool-water species, in a steadily warming Chesapeake. The indirect impacts of warming on SAV species are more complex and difficult to predict and are likely to trigger relatively sudden, unpredictable changes, including increased abundances of thermo-tolerant species and the introduction of subtropical species, particularly *Halodule wrightii*, which currently persists in Back Sound, North Carolina (Kenworthy 1981). In contrast, it is difficult to accurately forecast the impacts of climate warming on SAV in the freshwater regions of the Chesapeake Bay, where temperature effects on plant metabolism may significantly interact with other environmental changes such as salinity and eutrophication (Ryan 1991)."

CURRENTLY FUNDED STUDIES ASSESSING CLIMATE-RELATED IMPACTS TO SAV IN CHESAPEAKE BAY

1. SAV and Climate Change Modeling Project

Following the development and completion of TS III, the CBP supported a multi-institutional effort that synthesized over 30 years of SAV, water quality, and land-use data. Results of the study empirically demonstrated that management efforts to reduce nutrient pollution were responsible for the recovery of tens of thousands of acres of SAV in the Bay. While the validation of environmental policy is rewarding and provides necessary incentive to stay the course to ensure additional future recovery, the role of emerging climate stressors was not included or accounted for in this study, and the question of these threats to the Chesapeake Bay ecosystem, and to SAV specifically, still lingers.

As such, the SAV Workgroup recently collaborated with CBP's Scientific, Technical Assessment, and Reporting (STAR) team and Climate Resiliency Workgroup (CRWG) to obtain Goal Team Implementation (GIT) funding for a project to address the role of climate stressors on Chesapeake Bay SAV, including warming temperatures, rising sea levels, chronic low oxygen concentrations, and increased runoff driven by greater precipitation and more frequent, intense storm activity. This project was awarded to Dr. Chris Patrick and his team at VIMS with a sub-award granted to Dr. Jon Lefcheck at the Smithsonian Environmental Research Center (SERC). Balancing nutrient management strategies with emerging stressors will be a significant challenge for the Chesapeake Bay management community. Complicating this task will be the variety of SAV species in the Bay and their potentially contrasting responses, as was demonstrated during the 2019 Bay-wide SAV survey. The excessive precipitation in 2018 and 2019 increased nutrient loading to the Bay and also affected salinities. This had a dramatic and negative impact on SAV in the mid to southern, saltier portion of the Bay in 2019 where thousands of acres of SAV were lost, but SAV in the upper portion of the Bay and tributaries continued to expand in most areas. This does not suggest that freshwater SAV communities are impervious to poor water quality; there is some anecdotal evidence that species diversity has decreased in recent years in some of the

Bay's freshwater areas suggesting that water quality changes have in fact affected these communities. It also highlights the necessity to identify the ecological tipping points or levels of stress these communities can endure before they collapse. Furthermore, it suggests that it may be beneficial to tailor future management strategies to the various SAV communities present in the Bay.

Specifically, the objective of this project is to model interactions between nutrient loading and emerging climate stressors, including warming temperatures, oxygen minimum zones, sea-level rise, greater precipitation, and reduced water clarity in determining future SAV abundance and recovery potential, and to determine species and community-level tipping points.

Final project products will include a detailed report of model outcomes and potential SAV recovery trajectories under various climate change scenarios. Additionally, a software application will be developed for use by the Chesapeake Bay research and management community that will allow users to explore and determine the relative impact of various stressors on future community-specific SAV abundance. The software application will be developed with the flexibility to determine site-specific SAV restoration potential in future versions. [Text copied directly from project RFP.]

Although only approximately six months into their study, the team working on the SAV and Climate Modeling project has already yielded important results. Those results are included here with the caveat that this information is preliminary and not yet peer-reviewed, and that on-going analyses may yield results that complicate present interpretation of model outputs. Regardless, internal discussions suggested that the results to date were worth including as they may illuminate additional research needs and management responses. To our benefit, the VIMS team is also simultaneously working on a widgeon grass specific project that complements the SAV and Climate project. Together, these two studies have begun to answer questions related to the impact of rising water temperatures on Chesapeake Bay SAV. A series of these questions were posed to the team; the questions and responses are summarized here, with some additional commentary included for clarity provided by the chapter authors.

Q1: What do preliminary analyses suggest about the impacts of temperature on the various SAV communities in the Bay? Do the communities respond differently?

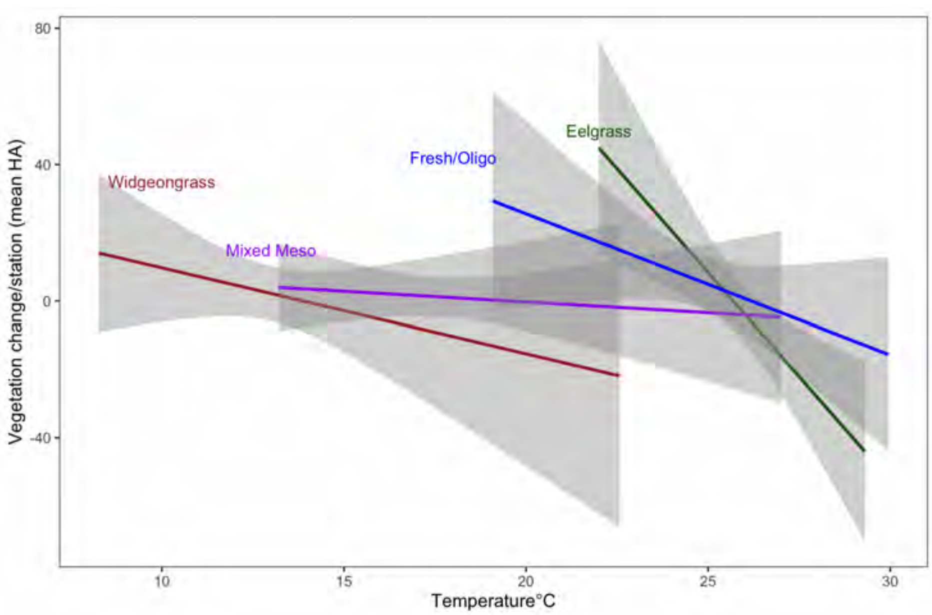
R1: For this study, the Bay's SAV communities were clumped into four main groups. These include Eelgrass monoculture, Widgeon grass monoculture, Mixed Mesohaline, and Oligohaline/Tidal Fresh. Our Structural Equation Model (SEM) results suggest that temperature affects multiple SAV communities in the Chesapeake, but the strength of the effect varies over space and time. SAV communities respond differently to temperature in the sense that temperature at different times of the year and previous year affects SAV in different ways. Regardless, temperature always has a negative effect, and the strength varies across the bay.

Community	Is there a temperature effect on annual change?	Is there a temperature effect on large meadows?	Are nutrient effects on SAV stronger than temperature effects?	Are salinity/ water clarity effects on SAV stronger than temperature effects?	Notes:
Eelgrass monoculture	Yes, Summer temps(last year) & spring temps (this year)	Yes, Summer temps (last year)	No, but chl-a_{spring} is important also	Possibly, summer salinity and secchi are equivalent to temp effects	$Temp_{sum\ y1}$ can swamp out other effects
Widgeon grass monoculture	No	Yes, Spring temps have tiny effect	Yes, TN has direct negative effect	Yes, high summer salinity promotes regrowth	$Temp_{spring}$ does contribute to elevated chl-*a* and lower water clarity (indirect effect)
Mixed Mesohaline	Yes, Summer temps (min, this year)	No	Possibly, TP has similar negative effect	Yes, last year's salinity maximum has strongest negative effect	Only community where temp is in change model but not area model
Oligohaline/ Tidal Fresh	Yes, Summer temps (last year)	Yes, Summer temps(last year)	No, but TP_{summer} does have strong negative effect	No, but Summer chl-*a* has a negative effect	Temp effects may be via effects on the cyanobacteri a!

To simplify communication of the results, model outcomes are further displayed in the following graph. Temperature is on the x-axis, but note that the variable changes for each community assemblage; significant temperature predictors were used for each.

- Widgeon grass monoculture: Spring mean temp
- Eelgrass monoculture: Summer last year median temp
- Mixed mesohaline: Summer min temp
- Fresh/oligohaline: Summer last year mean temp

The y-axis value is the mean change in vegetation area per station, in hectares. Communicating the difference in community assemblage by slope clarifies the ultimate message that eelgrass monocultures and tidal fresh/oligohaline communities clearly have a stronger (negative) response to temperature than widgeon grass monocultures or mixed mesohaline communities. While extensive research has shown that eelgrass is a cold water plant physiologically susceptible to high temperature extremes, it is not immediately clear why the tidal fresh/oligohaline community is also showing a significant negative response to increased temperatures. The majority of the plants in the freshwater regions of Chesapeake Bay (there are over a dozen freshwater SAV species in the Bay) are found throughout freshwater systems of the southeastern United States, suggesting they should be tolerant to heat extremes. One possible explanation, therefore, and as noted in the table above, is that the negative response in the tidal fresh/oligohaline community may be a result of cyanobacteria expansion in increasingly warm freshwaters of the Chesapeake. If this is the case, the effect is likely indirect and a result of shading rather than a physiological response and is in line with what Arnold et al. suggested in TS III regarding the plethora of unknown stressors that Chesapeake Bay SAV has in store as the climate warms. The impact of cyanobacteria on freshwater SAV are discussed later in this chapter.



Q2: Do other stressors have a synergistic effect with temperature on Chesapeake Bay SAV, or does temperature stand alone in its impact?

R2: Actual synergistic effects (i.e., temp * light effects) have not been evaluated, but that is a potential analytical option that has been discussed. Other stressors have been evaluated in the models, however, as indicated in the table above. Temperature is never the sole predictor of annual vegetation change across the Bay's SAV communities. When using the area-change model developed for this project (this model is more responsive to change in large meadows), temperature is overwhelmingly the strongest predictor of negative change in eelgrass monocultures and in the tidal fresh/oligohaline community, but a comparison of the magnitude of the effect size provides information on the relative importance of other variables as well. These are included in the table above and show that nutrients and clarity do, at times, have an equal or greater effect than temperature.

Temperature also has indirect effects on SAV in some of the models used. Specifically, high spring temperatures contribute to elevated chl-*a* and decreased water clarity (Secchi) in the widgeon grass monoculture analyses. Nutrient levels are more important than temperature in this case, but temperature does play a role in the biggest predictor of widgeon grass loss, which is high chl-a levels. Temperature similarly contributes to chl-a in the tidal fresh/oligohaline zone, but chl-a is less important in this model than in the widgeon grass monoculture model.

Q3: Is there sufficient certainty in the summarized research findings to support asking for further nutrient and sediment reductions for increased water clarity to offset the impacts of rising tidal water temperatures?

R3: Yes, there is sufficient certainty to support asking for further nutrient and sediment reductions not just to offset the temperature impacts for eelgrass monocultures and tidal fresh/oligohaline SAV communities, but to reduce the general impacts from above-average rain years like 2018-2019. Unmanaged nutrient inputs will surely exacerbate the effects of temperature extremes. The evidence for this lies within our SEMs that show, in each of the SAV communities where temperature is a significant predictor, that it is never the *only* significant predictor of change. Specifically, nutrient levels and/or water clarity variables frequently have either equivalent or greater effects on annual SAV change.

Outside of the direct comparison to temperature effects and more to the general importance of continued nutrient reductions, the baywide widgeon grass research also being conducted by VIMS nearly shows this on its own. Widgeon grass currently makes up approximately 40% of baywide SAV and is extremely sensitive to poor springtime water clarity. A significant proportion of recent SAV "recovery" over the last two decades is clearly correlated with nutrient reductions. Specifically, the two largest SAV acreage peaks that have occurred since the baywide aerial survey began in 1984 (2002-2003 & 2014-2016) are predominantly widgeon grass driven and widgeon grass clearly responds to both N and P (non-point source N, point-source P from the watershed) and chl-*a* (phytoplankton blooms) reductions. Widgeon grass recovery occurs almost exclusively in high salinity conditions (wherein low river flow/rainfall facilitates high water clarity).

Q4: How do Nitrogen, Phosphorus, and Total Suspended Solids impacts differ across the Bay and between SAV communities?

R4: Analyses indicate that the importance of each varies across the bay. Nitrogen appears to be most important in the lower bay. It affects both eelgrass and widgeon grass *via* chl-*a* and also affects widgeongrass directly, likely from epiphyte loading (epiphytes grow in response to high N) early in the growing season. Phosphorus does contribute to chl-*a* in the widgeongrass and eelgrass models even though it seems to be more important in the fresh and mesohaline regions, where summer TP actually has direct interactive effects on last year's grass coverage to negatively affect SAV acreage. TSS did not play a significant role in our models, but that doesn't necessarily mean it's not important. Rather it may reflect a lack of data.

Q5: Do you envision a set of circumstances in which we can keep a viable population of eelgrass in Chesapeake Bay in the coming decade(s) given increasing temperatures above survival thresholds for this species?

R5: The combined effect size of temperature variables and water clarity variables are nearly equivalent in the eelgrass model in terms of year to year change. However, when the eelgrass area change model (which is driven more by large meadows) is employed, the previous summer median temperature is the only significant predictor of area change and the effect is quite strong. In fact, the negative effect size is larger than the positive effect of the grass that was there the year before. This indicates that temperature extremes have the ability to completely outweigh any water clarity effects when we look at change over large areas as opposed to proportional change across all areas, even areas with sparse SAV.

With that in mind, the answer may still be yes. Temperature extremes would need to occur practically every year to completely extirpate what we have now, theoretically, if temperature were the only stressor. Eelgrass in the Bay continues to respond positively to nutrient reductions/water clarity improvements, so management of those is absolutely essential moving forward to maintain eelgrass populations.

2. Cyanobacteria Study

Another issue of emerging concern regarding increasing water temperatures and the Chesapeake's SAV is the recent proliferation of benthic cyanobacteria in the Bay's freshwater regions. Benthic cyanobacteria, originally identified in the Bay as *Lyngbya* and *Oscillatoria,* became prevalent on the Susquehanna Flats beginning in 2004, and reports of their presence in the SAV beds of other tidal fresh and oligohaline tributaries of the upper and mid-Bay are becoming more frequent as well. The expansion of benthic cyanobacteria is thought to be facilitated in part by increasing water temperatures. Because these cyanobacteria fix atmospheric nitrogen into a biologically useful form of N, they could be altering the role of SAV beds where they co-occur as net nitrogen sinks, seasonally turning them into nitrogen sources instead. If so, this may exacerbate the complexity of management actions needed to support SAV productivity in the Bay.

Additionally, the overgrowth of benthic cyanobacteria atop SAV leads to reduced light availability and inhibition of gas exchange, which may decrease SAV photosynthetic rates and increase sediment anoxia and nutrient fluxes (Watkinson et al. 2005; O'Neil et al. 2012; Tiling & Proffitt 2017). As mentioned in the discussion of the SAV and Climate Modeling study above, this may explain the negative effect of increasing temperatures on freshwater SAV. Interestingly though, cyanobacteria blooms are far more prevalent on the Susquehanna Flats SAV bed than anywhere else in the Bay, and the bed has continued to expand in acreage and density regardless of their presence.

Aside from serving as a possible explanatory variable in the SAV and Climate Modeling study, these co-occurring cyanobacteria have not been taken into consideration in previous studies of ecological and biogeochemical dynamics on the Susquehanna Flats or other regions of Chesapeake Bay. Furthermore, it is unclear whether these cyanobacteria produce harmful toxins, as documented in other geographic regions.

As such, researchers and managers from the University of Maryland Center for Environmental Science, St. Mary's College of Maryland, and the Maryland Department of Natural Resources were recently funded by Maryland Sea Grant to conduct a study that aims to better understand the causes and effects of increasing benthic cyanobacteria abundance in Chesapeake Bay with an emphasis on their impact on SAV and nutrient dynamics. The team will address the following questions: 1) what factors are driving benthic cyanobacteria proliferation on the Susquehanna Flats and other regions of Chesapeake Bay (ie. increasing water temperature?), 2) what effect do benthic cyanobacteria have on ecosystem processes, including SAV and nutrient dynamics, and 3) are benthic cyanobacteria producing toxins known to cause adverse reactions in humans or animals?

It is anticipated that the results of this study will generate important scientific insights about the role of benthic cyanobacteria in shallow, tidal fresh and oligohaline ecosystem recovery dynamics and will inform management efforts aimed at protecting human and ecological health in Chesapeake Bay. [Much of this text was copied directly from the project proposal but information was added in for clarity and comparison to the SAV and Climate Modeling study by the chapter authors.]

WHAT IS BEING DONE TO DIRECTLY RESTORE CHESAPEAKE BAY SAV?

While there are multiple stressors acting against the sustained recovery of SAV in Chesapeake Bay, including rising water temperatures, SAV restoration practitioners have seen increasing success rates in small-scale, direct SAV restoration efforts. Historically, direct restoration in Chesapeake Bay has proven costly and largely ineffective because most efforts centered on the restoration of a single species: eelgrass. As discussed previously, eelgrass is a cool water species near its southern limit in the Chesapeake Bay. Although it can tolerate some turbidity and some heat stress, it doesn't tolerate both simultaneously. As Lefcheck et al. (2017) described in recent research, "declining clarity has gradually reduced eelgrass cover the past two decades, primarily in deeper beds where light is already limiting. In shallow beds, however, reduced visibility exacerbates the physiological stress of acute warming, leading to recent instances of decline approaching 80%. While degraded water quality has long been known to influence underwater grasses worldwide, they demonstrated a clear and rapidly emerging interaction with climate change (increasing temperatures)."

In 2011, CBP's STAC conducted a review of Chesapeake Bay SAV restoration efforts. In line with what Lefcheck et al. later found in 2017, the review team, led by Mark Luckenbach at VIMS, had the following to say: "Our review generally supports the techniques used for planting and monitoring SAV. Evidence from the York and James rivers and from Virginia's Coastal Bays supports the premise that SAV beds can be successfully restored using these techniques where water quality is sufficient. The majority of direct SAV restoration efforts were undertaken with eelgrass *Zostera marina*. The rationale for focusing most of the effort on this species—its wide distribution, established restoration techniques and historic low levels—was sound. However, if more resources had been available to develop techniques, direct restoration with other species would have been desirable.

The primary means of selecting restoration sites was a GIS-based decision tool, which incorporated information on water quality, water depth, current and historical SAV distribution, important fisheries habitat, and potential disturbance from clam fisheries. Though this site selection model was arguably state-of-the-art at the time it was developed, it fell short in meeting its intended use. A review of the model's effectiveness revealed that it was adequate for predicting sites where germination of SAV seeds would occur, but not for predicting persistence of beds beyond one year. Shortcomings of the model include (*i*) limitations on the data available to parameterize it, (*ii*) failure to include temperature as a stressor, and (*iii*) perhaps most importantly, reliance on multi-year average water quality, rather than variances and even extremes. This latter limitation was evident in numerous instances when data used to select restoration sites were collected in dry or average rainfall years and restoration was then followed by high rainfall (and thus poor water quality) years. The need to incorporate longer-term data sets, multiple stressors and environmental extremes into the site selection model is now apparent."

With the recent success of small-scale restoration efforts in tidal fresh, oligohaline, and mesohaline environments (facilitated in part by research conducted at Anne Arundel Community College and Maryland Department of Natural Resources) and insights from Lefcheck et al. (2017) and Luckenbach et al. (2011), the SAV Workgroup proposed in 2020 the development of a small-scale SAV restoration protocol and technical guidance manual (and associated outreach materials) and obtained Goal Implementation Team funding to do so. The project was contracted to Green Fin Studios with a sub-contract awarded to SAV expert Cassie Gurbisz, St. Mary's College of Maryland and was completed in November, 2021.

The intended audience for *Small-scale SAV Restoration in Chesapeake Bay: A Protocol and Technical Guidance Manual* is federal and state agencies, local jurisdictions, and non-government organizations, such as Riverkeeper and other watershed organizations. The ultimate purpose of the effort is to accelerate SAV recovery in Chesapeake Bay and its tidal tributaries, to the extent feasible, by supplementing natural recovery with direct restoration efforts in which seeds or mature plants are planted in areas where water quality is deemed sufficient for growth and expansion, but where a seed bank or persistent population is not currently present.

In the manual, guidance is provided for multiple species to facilitate plantings in all salinity regimes. Wild celery is recommended for tidal fresh and oligohaline restoration projects. Mesohaline species include widgeon grass, sago pondweed, and redhead grass. Polyhaline species includes widgeon grass and eelgrass. Although restoration efforts with eelgrass have been largely unsuccessful in Chesapeake Bay, restoration in the nearby coastal bays of Virginia have done astonishingly well because of the higher water quality in those Bays, indicating that with improved water quality/clarity conditions, all is not lost for eelgrass in the Chesapeake. With proper management and sustained efforts to improve water clarity, eelgrass will be able to more effectively withstand heat stress during extreme events. This is also evidenced by the thriving populations of eelgrass further south in North Carolina. The water there is warmer than in the Chesapeake, but clearer, and consequently the eelgrass can maintain its populations.

E. EVALUATION

Key Findings:

- There are three primary symptoms of climate change that will directly affect Chesapeake Bay SAV: rising water temperatures, increased CO_2 concentrations, and sea level rise.

- Temperature impacts to eelgrass are well understood and without drastic improvements in water clarity or a reversal of warming trends, viable populations of eelgrass will likely be extirpated from Chesapeake Bay.

- Temperature impacts to other Chesapeake Bay SAV species are not as well studied but based on available data, appear to be less dramatic than those to eelgrass. With that said, current research and preliminary results suggests that increasing temperatures do negatively impact all Chesapeake Bay SAV communities to some extent.

- The CO_2 fertilization effect may counterbalance some of the impacts from warming, but unknowns associated with invasive species, pathogens, cyanobacteria, etc. may set that balance awry.

- Management efforts (ie. the Chesapeake Bay TMDL) that have reduced N and P in the Chesapeake have facilitated the (partial) recovery of SAV.

- The currently funded climate and SAV modeling project will be instrumental in answering many of our questions.

- The benthic cyanobacteria project will (hopefully) confirm if temperature increases are facilitating the spread of benthic cyanobacteria throughout the freshwater regions of the Bay, and if that spread is affecting SAV.

- SAV restoration efforts for diverse species may mitigate some of the loss of SAV from areas unable to recover without a seed source.

Management Implications:

As discussed, SAV provides multiple ecosystem services and co-benefits. These include the provision of food, habitat, refuge, and nursery grounds for commercially, recreationally, and ecologically important fish, shellfish, and a variety of invertebrates. Even waterfowl use SAV beds extensively. The submerged plants also take in and process excess CO_2 and nutrients, which helps mitigate impacts from climate change by sequestering carbon and decreasing the opportunity for macroalgae and phytoplankton blooms, including HABS, by removing their fuel source. As they take up CO_2 and release O_2, SAV beds not only oxygenate the water column; they also buffer the impacts of coastal acidification on the vulnerably shelled organism either living within the beds or nearby. Their physical presence in the water column baffles current and wave energy, reducing shoreline erosion. These are all ecosystem services – services provided to the growing human population in the watershed and beyond by the Bay's SAV - that could be lost with the continued degradation of water quality and impacts of climate stressors, including rising temperatures.

The continued loss of the Bay's SAV and ecosystem services that it provides could have significant management implications and profound economic consequences (Lefcheck et al. 2017), particularly regarding fisheries. The Bay's most economically significant fishery – blue crabs (*Callinectus sapidus*) – is directly dependent on eelgrass. In the spring, planktonic blue crab larvae migrate into the Bay assisted by winds and tides from offshore. The larvae rely heavily on the physical structure of eelgrass as a cue to settle. Juvenile blue crabs then proceed to shelter in the eelgrass beds and use the protection of the SAV for habitat and forage. In areas where eelgrass is lost and not replaced by widgeon grass, juvenile blue crabs will be significantly more susceptible to predation. In areas where widgeon grass does replace eelgrass, there remains the question of timing. Eelgrass begins to emerge from the sediment in December/January and reaches peak biomass in May. Widgeon grass, on the other hand, does not start to emerge until later in the spring, generally in April, and reaches peak biomass in July/August. Even in areas where widgeon grass does replace eelgrass, this shift in timing of available habitat when juvenile blue crabs are entering the Bay in the spring could have significant implications for population level survival. It could also force larvae to travel farther into the Bay in search of widgeon grass before settling; the more time in the water column, the bigger the odds of predation.

Of course, blue crabs do use widgeongrass and other mesohaline SAV species when available. Widgeon grass is the most abundant and widespread SAV species in the Bay. Unfortunately, it is susceptible to water quality degradation, like other SAV, but tends to respond more dramatically, leaving juvenile and adult blue crabs alike vulnerable to limited habitat availability when it crashes. Following the ~42,000-acre loss of SAV from 2018 to 2019, and the additional ~4,000-acre loss from 2019 to 2020, the 2020 and 2021 Blue crab winter dredge surveys both yielded significantly reduced numbers of juvenile blue crabs. The expansive loss of Chesapeake Bay SAV in 2019 and 2020 was likely a factor in that reduction.

Likewise, fisheries throughout the Bay would be impacted by a loss of SAV associated with increasing temperatures. While eelgrass is clearly the most vulnerable Chesapeake Bay SAV species, the information provided in TS III and the preliminary results of the SAV and Climate Modeling study suggest that all of the Bay's SAV communities are at least somewhat susceptible to increasing water temperatures. Where direct impacts are less severe, indirect impacts may prove equally damaging. Indirect impacts associated with increasing temperatures include unknowns like

- changes in rainfall and the frequency and intensity of storms,
- increased eutrophication,
- proliferation of epiphytes,
- increased shoreline armoring,
- higher sediment sulfide levels,
- changes in microbiota that support SAV productivity
- invasive species,
- expanding *Lyngbya* and other filamentous cyanobacteria
- changes in grazer types and abundance
- pathogens (ie. *Labyrinthula spp*.)

All of these could impact SAV productivity and consequently the animals that rely on it for forage and habitat, from the smallest of forage fish to larger recreationally important species like Largemouth bass. The bass-fishing industry in the upper Bay (Susquehanna Flats) and on the Potomac River are reliant on SAV health and productivity, for example.

Aside from the ecologically and commercially significant consequences of fisheries declines associated with SAV loss, there is also the practical concern of not being able to reach Bay-wide or segment-specific SAV goals. SAV recovery goals were established, of course, to ensure that the ecological benefits of SAV were maintained. To ensure that segment-specific goals are met and based on differences in SAV community responses to increasing temperatures, it may be necessary to consider more regionally-focused management actions or to concentrate BMP implementation and restoration efforts in areas where SAV is most impaired.

To manage the impacts of increasing temperatures on freshwater plants, we require not only a better understanding of individual freshwater species' heat tolerances, but also how those species will be affected by grazers and other microbiota that may become established as a result of increasing temperatures. That, and how the timing differential between eelgrass and widgeon grass will affect blue crab productivity are two research needs identified by the SAV Workgroup associated with the issue of rising Bay water temperatures.

While questions remain regarding the impact of rising temperatures on SAV and the effects of climate change in general, it is clear that the single most effective action that can be taken to protect Chesapeake Bay SAV is to sustain and accelerate improvements in water quality and clarity through N, P, and TSS load reductions and appropriate BMP implementation. Chesapeake Bay SAV will be substantially more resilient to all climate stressors if water clarity is maximized.

REFERENCES CITED

Amano, M., S. Iida, and K. Kosuge. 2012. Comparative studies of thermotolerance: different modes of heat acclimation between tolerant and intolerant aquatic plants of the genus Potamogeton. Annals of Botany. 109: 2: 443-452.

Anderson, R. R., 1969. Temperature and rooted aquatic plants. Chesapeake Science 10:157-164.

Arnold, T.M., R.C. Zimmerman, K.A.M. Engelhardt, and J.C. Stevenson. 2017. Twenty-first century climate change and submerged aquatic vegetation in a temperate estuary: the case of

Chesapeake Bay, Ecosystem Health and Sustainability. http://dx.doi.org/10.1080/20964129.2017.1353283

Barko, J.W., Smart, R.M. 1981. Comparative influences of light and temperature on the growth and metabolism of selected submersed freshwater macrophytes. Ecological Monographs 51:219-236.

Bartleson, R.D., M.J. Hunt, and P.H. Doering. 2014. Effects of temperature on growth of *Vallisneria americana* in a sub-tropical estuarine environment. Wetlands Ecology and Management. 22: 571-583.

Beser, T.M. 2007. Effects of thermal effluent from C.P. Crane Generating Station on submersed aquatic macrophyte communities in the Saltpeter-Dundee Creek system. MS Thesis, University of Maryland College Park. Pp. 118.

Blake, Rachael E., Duffy, J. Emmett. 2010. Grazer diversity affects resistance to multiple stressors in an experimental seagrass ecosystem. OIKOS. 119: 10: 1625-1635.

Campbell, S.J., L.J. McKenzie, and S. P. Kerville. 2006. Photosynthetic responses of seven tropical seagrasses to elevated seawater temperature. Journal of Experimental Marine Biology and Ecology. 330: 2: 455-468.

Cao, Y., L. Wei, and E. Jeppesen. 2014. The response of two submerged macrophytes and periphyton to elevated temperatures in the presence and absence of snails: a microcosm approach. Hydrobiologia. 738: 1: 49-59.

Carr, J. A., P. D'Odorico, K.J. McGlathery, and P.L. Wiberg. 2012. Modeling the effects of climate change on eelgrass stability and resilience: future scenarios and leading indicators of collapse. Mar Ecol Prog S 448: 289-301.

Chesapeake Bay Program, 2009, Chesapeake Bay Executive Order—About the Executive Order: accessed April 9, 2013, at http://executiveorder.chesapeakebay.net/page/About-the-Executive-Order.aspx.

Crow, G.E. 1993. Species diversity in aquatic angiosperms – latitudinal patterns. AQUATIC BOTANY Volume: 44 Issue: 2-3 Pages: 229-258

Ding, H., and A.J. Elmore. 2015. Spatio-temporal patterns in water surface temperature from Landsat time series data in the Chesapeake Bay, USA. Remote Sensing of Environment. 168: 335-348.

Evans, A. S., K. L. Webb, and P. A. Penhale. 1986. Photosynthetic temperature acclimation in two coexisting seagrasses, *Zostera marina* L. and *Ruppia maritima* L. Aquat. Bot. 24: 185-197.

Garcia, R., M. Holmer, C.M. Duarte, and M. Nuria. 2013. Global warming enhances sulphide stress in a key seagrass species (NW Mediterranean). Global Change Biology. 19: 12: 3629-3639.

Goodman, J.L., K.A. Moore and W.C. Dennison. 1995. Photosynthetic Responses of Eelgrass (*Zostera marina* L) to light and Sediment Sulfide in a Shallow Barrier-Island Lagoon. Aquatic Botany. 50: 1: 37-47.

Grace, J.B., and L.J. Tilly. 1976. Distribution and abundance of submerged macrophytes, including *Myriophyllum spicatum* L. (Angiospermae), in a reactor cooling reservoir. Archiv f. Hydrobiologie 77:475-487.

Haag, R.W., and P.R. Gorham. 1977. Effects of thermal effluent on standing crop and net production of *Elodea canadensis* and other submerged macrophytes in Lake Wabamun, Alberta. The Journal of Applied Ecology 14:835-851.

Haag, R.W. 1983. Emergence of seedlings of aquatic macrophytes from lake sediments. CANADIAN JOURNAL OF BOTANY-REVUE CANADIENNE DE BOTANIQUE Volume: 61 Issue: 1 Pages: 148-156

Haller, W.T. and D.L. Sutton. 1975. Community structure and competition between *Hydrilla* and *Vallisneria*. Hyacinth Control J. 13: 48-50.

Hammer, K.J., J. Borum, H. Hasler-Sheetal, E.C. Shields, K. Sand-Jensen, K.A. Moore. 2018. High temperatures cause reduced growth, plant death and metabolic changes in eelgrass *Zostera marina*. Marine Ecology Progress Series 604: 121-132. https://doi.org/10.3354/meps12740

Hay, F., Probert, R., and M. Dawson. 2008. Laboratory germination of seeds from 10 British species of Potamogeton. Aq. Bot. 88(4): 353-357.

Hershner, C., K.J. Havens. 2008. Managing invasive aquatic plants in a changing system: strategic consideration of ecosystem services. Conservation Biology 22(3):544-550.

IPCC 2014. "Climate Change 2014: Synthesis Report." In Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer, 151pp. Geneva: IPCC.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MassonDelmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Jarvis, J.C., and K.A. Moore. 2008. Influence of environmental factors on *Vallisneria americana* seed germination. Aq. Bot. 88(4): 283-294.

Johnson, M.R., Williams, S.L., Lieberman, C.H., et al. 2003. Changes in the abundance of the seagrasses *Zostera marina* L. (eelgrass) and *Ruppia maritima* L. (widgeongrass) in San Diego, California, following an El Nino event. Estuaries. 26: 1:106-115.

Kemp, W.M., W.R. Boynton, J.C. Stevenson, R.W. Twilley and J.C. Means. 1983. The decline of submerged vascular plants in upper Chesapeake Bay: summary of results concerning possible causes. Marine Tech. Society Journal 17:78-89.

Korschgen, C.E., and W.L. Green. 1988. American wildcelery (*Vallisneria americana*): Ecological considerations for restoration. U.S. Fish and Wildlife Service, Fish and Wildlife Technical Report 19. Jamestown, ND: Northern Prairie Wildlife Research Center Online.

Lacoul, P. and B. Freedman. 2006. Environmental influences on aquatic plants and freshwater ecosystems. Environ. Rev. 14: 89–136

Landry, J.B. (ed). T.A. Arnold, K.A.M. Engelhardt, R.R. Golden, C. Gurbisz, W.M. Kemp, C.J. Kennedy, S. Kollar, K.A. Moore, M.C. Neel, C. Palinkas, C.J. Patrick, N.B. Rybicki, E.C. Shields, J.C. Stevenson, C.E. Tanner, L.A. Wainger, D.E. Weller, D.J. Wilcox, and R.C. Zimmerman. 2016. Chesapeake Bay Submerged Aquatic Vegetation: A Third Technical Synthesis. United States Environmental Protection Agency for the Chesapeake Bay Program.

Lefcheck, J.S., D.J. Wilcox, R.R. Murphy, S.R. Marion, and R.J. Orth. 2017. Multiple stressors threaten the imperiled coastal foundation species eelgrass (*Zostera marina*) in Chesapeake Bay, USA. Global Change Biology https://doi:10.1111/gcb.13623

Lefcheck, J.S., R.J. Orth, W.C. Dennison, D.J. Wilcox, R.R. Murphy, J. Keisman, C. Gurbisz, M. Hannam, J.B. Landry, K.A. Moore, C.J. Patrick, J. Testa, D.W. Weller, R.A. Batiuk. 2018. Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region. *Proceedings of the National Academy of Sciences* 115(14): 358-3662

Levitus, S., J.I. Antonov, J.L. Wang, et al. 2001. Anthropogenic warming of Earth's climate system. Science. 292: 5515: 267-270.

Luckenbach, M., L. Wainger, D. Weller, S. Bell, M. Fonseca, K. Heck, H. Neckles, M. Smart, C. Pickerell. 2011. Evaluation of the Effectiveness of SAV Restoration Approaches in the Chesapeake Bay: A program review requested by the Chesapeake Bay Program's SAV Workgroup and conducted by the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC).
Chesapeake Research Consortium, Inc. Publication Number: 11-03

Madsen, J.D. and M.S. Adams. 1988. The germination of *Potamogeton pectineus* tubers – environmental-control by temperature and light. CANADIAN JOURNAL OF BOTANY-REVUE CANADIENNE DE BOTANIQUE. Volume: 66 Issue:12 Pages: 2523-2526

Madsen, J., Adams, M., 1989. The light and temperature dependence of photosynthesis and respiration in *Potamogeton pectinatus* L. Aquat. Bot. 36, 23–31.

Marba, N., and C.M. Duarte. 1997. Interannual changes in seagrass (*Posidonia oceanica*) growth and environmental change in the Spanish Mediterranean littoral zone. Limnology and Oceanography. 42:5: 800-810.

Marsh, J. A., W. C. Dennison, and R. S. Alberte. 1986. Effects of temperature on photosynthesis and respiration in eelgrass (*Zostera marina* L.). J. Exp. Mar. Biol. Ecol. 101: 257-267.

Mckee, D., K. Hatton, J.W. Eaton, D. Atkinson, A. Atherton, I. Harvey, B. Moss. 2002. Effects of simulated climate warming on macrophytes in freshwater microcosm communities. Aquatic Botany. 74: 1: 71-83.

Meehl, G.A., and Thomas F. Stocker. 2007. Global Climate Projections. Intergovernmental Panel on Climate Change: Climate Change 2007: the Physical Science Basis. 747-845.

Moore, K.A., and J.C. Jarvis. 2008. Environmental factors affecting recent summertime eelgrass diebacks in the lower Chesapeake Bay: implications for long-term persistence. J Coast Res Spec Issue. 55: 135-147.

Moore, K.A., E.C. Shields, D.B. Parrish, and R.J. Orth. 2012. Eelgrass survival in two contrasting systems: role of turbidity and summer water temperatures. Marine Ecology Progress Series. 448: 247-258.

Moore, K.A., E.C. Shields, and D.B. Parrish. 2014. Impacts of Varying Estuarine Temperature and Light Conditions on *Zostera marina* (Eelgrass) and its Interactions with *Ruppia maritima* (Widgeongrass). Estuaries and Coasts. 37: 1: S20-S30.

Moyle, P. B. 2014. Novel Aquatic Ecosystems: The New Reality for Streams in California and Other Mediterranean Climate Regions. River Research and Applications. 30: 10: 1335-1344.

Najjar, R.G., C.R. Pyke, M.B. Adams, et al. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuaries Coastal and Shelf Science. 86: 1: 1-20.

Nichols S.A., and B.H. Shaw, B.H. 1986. Ecological life histories of the three aquatic nuisance plants, *Myriophyllum spicatum*, *Potamogeton crispus* and *Elodea canadensis*. Hydrobiologia 131:3-21.

Niu, S., P. Zhang, J. Liu, D. Guo, and Xiumei Zhang. 2012. The effect of temperature on the survival, growth, photosynthesis, and respiration of young seedlings of eelgrass *Zostera marina* L. Aquaculture. 350: 98-108.

Olesen, B., and T.V. Madsen, T.V. 2000. Growth and physiological acclimation to temperature and inorganic carbon availability by two submerged aquatic macrophyte species, *Callitriche cophocarpa* and *Elodea canadensis*. Functional Ecology 14:252-260.

Olsen, Y.S., and C.M. Duarte. 2015. Combined effect of warming and infection by *Labyrinthula* sp on the Mediterranean seagrass *Cymodocea nodosa*. Marine Ecology Progress Series. 532: 101-109.

Olsen, Y.S., M. Sanchez-Camacho, N. Marba, et al. 2012. Mediterranean Seagrass Growth and Demography Responses to Experimental Warming. Estuaries and Coasts. 35:5: 1205-1213.

Olsen, Y. S., M. Potouroglou, N. Garcias-Bonet, and C.M. Duarte. 2015. Warming Reduces Pathogen Pressure on a Climate-Vulnerable Seagrass Species. Estuaries and Coasts. 38: 2: 659-667.

O'Neil, J.M., T.W. Davis, M.A. Burford, and C.J. Gobler. 2012. The Rise of Harmful Cyanobacteria Blooms: Potential Role of Eutrophication and Climate Change. Harmful Algae 14:313-334.

Orth, R.J., and K.A. Moore. 1984. Distribution and Abundance of Submerged Aquatic Vegetation in Chesapeake Bay: An Historical Perspective. Estuaries (7)531-540. http://www.jstor.org/stable/1352058

Orth, R.J., S.R. Marion, K.A. Moore, and David J. Wilcox. 2010. Eelgrass (*Zostera marina* L.) in the Chesapeake Bay Region of Mid-Atlantic Coast of the USA: Challenges in Conservation and Restoration. Estuaries and Coasts. 33: 1: 139-150.

Orth, R.J., M.R. Williams, and R. Marion Scott, et al. 2010. Long-Term Trends in Submersed Aquatic Vegetation (SAV) in Chesapeake Bay, USA, Related to Water Quality. Estuaries and Coasts. 33: 5: 1144-1163.

Orth, R.J., Moore, K.A., Scott, R., et al. 2012. Seed addition facilitates eelgrass recovery in a coastal bay system. Mar. Ecol. Progr. Ser. 448: 197-207.

Orth, R.J., W.C. Dennison, J.S. Lefcheck, C. Gurbisz, M. Hannam, J. Keisman, J.B. Landry, K.A. Moore, R.R. Murphy, C.J. Patrick, J. Testa, D.E. Weller, D.J. Wilcox. 2017. Submersed aquatic vegetation in Chesapeake Bay: Sentinel species in a changing world. *BioScience* 67(8): 698-712

Pip, E. 1989. Water temperature and freshwater macrophyte distribution. Aquatic Botany 34:367-373.

Pulich, W.M. 1985. Seasonal Growth Dynamics of *Ruppia maritima* L SL and *Halodule-wrightii* Aschers in Southern Texas and Evaluation of Sediment Fertility Status. Aquatic Botany. 23: 1: 53-66.

Rice, K.C., and J.D. Jastram. 2015. Rising air and stream-water temperatures in Chesapeake Bay region, USA. Climate Change. 128: 1-2: 127-138.

Rooney, N., and J. Kalff. 2000. Inter-annual variation in submerged macrophyte community biomass and distribution: the influence of temperature and lake morphometry. Aquatic Botany 68:321-335.

Rosenzweig, M.L. 2003. Win-Win Ecology: How Earth's Species Can Survive in the Midst of Human Enterprise. Oxford University Press, New York, NY. ISBN 0-19-515604-8
Ryan, M.G. 1991. Effects of climate change on plant respiration. Ecological Applications 1:157-167.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H. 2000. Global biodiversity scenarios for the year 2100. Science 287:1770-1774.

Santamaria, L., and W. van Vierssen. 1997. Photosynthetic temperature responses of fresh- and brackish-water macrophytes: a review. Aquatic Botany 58:135-150.

Seekell, D.A. and M.L. Pace. 2011. Climate change drives warming in the Hudson River Estuary, New York (USA). Journal of Environmental Monitoring. 13: 8: 2321-2327.

Shields, E.C, D. Parish, and K. Moore. 2019. Short-Term Temperature Stress Results in Seagrass Community Shift in a Temperate Estuary. Estuaries and Coasts https://doi.org/10.1007/s12237-019-00517-1

Shields, E.C., K.A. Moore, and D.B. Parish. 2018. Adaptations by Zostera marina Dominated Seagrass Meadows in Response to Water Quality and Climate Forcing. Diversity https://doi:10.3390/d10040125

Short, F.T., and H.A. Neckles.1999. The effects of global climate change on seagrasses. Aquatic Botany. 63: 3-4: 169-196.

Somero, G.N. 2002. Thermal physiology and vertical zonation of intertidal animals: Optima, limits, and costs of living. Integrative and Comparative Biology 42:780-789.

Spencer, D.F. 1986. Early growth of *Potamogeton pectinatus* L. in response to temperature and irradiance: morphology and pigment composition. Aquatic Botany 26:1-8.

Spenser and Ksander 1992Stachowicz, J.J., S.J. Kamel, R.A. Hughes, and R. K. Grosberg. 2013. Genetic Relatedness Influences Plant Biomass Accumulation in Eelgrass (*Zostera marina*). American Naturalist. 181: 5:715-724.

Staver, K.W. 1984. Responses of epiphytic algae to nitrogen and phosphorus enrichment and effects on productivity of the host plant, *Potamogeton perfoliatus* L., in estuarine waters. M.S. Thesis. University of Maryland, CEES, Horn Point Laboratory.

Staver, L.W. and J.C. Stevenson. 1995. The impacts of the exotic species *Hydrilla verticillata* on the shallows in Chesapeake Bay. Pp. 364-370, In: Proceedings of Chesapeake Research Conference: "Toward a Sustainable Coastal Watershed", Norfolk, VA. Chesapeake Research Consortium Public. #149, Shady Side MD.

Staver, L.W., K.W. Staver and J.C. Stevenson. 1996. Nutrient inputs to the Choptank River Estuary: Implications for watershed management. Estuaries 19:342-358.

Stevenson, J.C. 1988. Comparative ecology of submersed grass beds in freshwater, estuarine and marine environments. Limnol. & Oceanogr. 33: 867-893.

Stevenson, J.C., L.W. Staver and K.W. Staver. 1993. Water quality associated with survival of submersed aquatic vegetation along an estuarine gradient. Estuaries 16:346-361.

Svensson, R. and M. Wigren-Svensson. 1992. Effects of cooling water discharge on the vegetation in the Forsmark Biotest Basin, Sweden. Aq. Bot. 42(2): 121-141.

Tanner, C., S. Hunter, J. Reel, T. Parham, M. Naylor,L. Karrh, K. Busch, R.R. Golden, M. Lewandowski, N. Rybicki, and E. Schenk. 2010. Evaluating a Large-Scale Eelgrass Restoration Project in the Chesapeake Bay. Restoration Ecology. 18: 4: 538-548.

Tiling, K. and C.E. Proffitt. 2017. Effects of *Lyngbya majuscula* blooms on the seagrass *Halodule wrightii* and resident invertebrates. Harmful Algae 62: 104-112.

Thayer, G. W., W. J. Kenworthy, and M. F. Fonseca. 1984. The ecology of eelgrass meadows of the Atlantic Coast: A community profile. U.S. Fish Wildl. Serv. FWS/OBS 84/02: 147.

Thomson, J.A., D.A. Burkholder, M.R. Heithaus, J.W. Fourqurean, M.W. Fraser, J. Statton, G.A. Kendrick. 2015. Extreme temperatures, foundation species, and abrupt ecosystem change: an example from an iconic seagrass ecosystem. Global Change Biology. 21: 4:1463-1474.

Watkinson, A.J., J.M. O'Neil, and W.C. Dennison. 2005. Ecophysiology of the bloom forming cyanobacterium *Lyngbya majuscula* in Moreton Bay, Australia. Harmful Algae 4: 697-715

Welch, P.S. 1952 Limnology. Second edition, McGraw-Hill Book Co. https://archive.org/details/limnology030682mbp

Wittyngham, S., Moderan, J., Boyer, K.E., 2019. Temperature and salinity effects on submerged aquatic vegetation traits and susceptibility to grazing. Aquatic Botany 158. https://doi.org/10.1016/j.aquabot.2019.05.004

Wood, R.J., Boesch, D.F., and V.S. Kennedy. 2001. Future consequences of climate change for the Chesapeake Bay ecosystem and its fisheries. Ed. McGinn. Paper presented at N.A. Conference: Symposium on Fisheries in a Changing Climate Location: PHOENIX, AZ Date: AUG 20-21, 2001. Fisheries in a Changing Climate. 2002. American Fisheries Society Symposium. 32: 171-183.

Yin, L., R. Zhang, Z. Xie, C. Wang, and W. Li. 2013. The effect of temperature, substrate, light, oxygen availability and burial depth on *Ottelia alismoides* seed germination. Aquatic Botany. 111: 50-53.

York, P. H., R.K. Gruber, R. Hill, P.J. Ralph, D.J. Booth, and P.I. Macreadie. 2013. Physiological and Morphological Responses of the Temperate Seagrass *Zostera muelleri* to Multiple Stressors: Investigating the Interactive Effects of Light and Temperature. PLoS ONE. 8(10): e76377.

Zimmerman, R. C., R. D. Smith, and R. S. Alberte. 1989. Thermal acclimation and whole plant carbon balance in *Zostera marina* L. (eelgrass). J. Exp. Mar. Biol. Ecol. 130: 93-109.

Zimmerman, R., V. Hill, C. Gallegos, and L. Charles. 2015. Predicting effects of ocean warming, acidification and water quality on Chesapeake region eelgrass. Limnology. Oceanograhy. 60: 1781-1804.

Zimmerman, R., Hill, V., Jinuntuya, M., Celebi, B., Ruble, D., Smith, M., Cedenol, T., Swingle, M. 2017. Experimental impacts of climate warming and ocean carbonation on eelgrass *Zostera marina*. Marine Ecology Progress Series 566: 1-15. https://doi.org/10.3354/meps12051

Zimmerman, R.C. 2021. Scaling up: Predicting the Impacts of Climate Change on Seagrass Ecosystems. Estuaries and Coasts. 44: 558–576. https://doi.org/10.1007/s12237-020-00837-7

Appendix H

Synthesis Element 4: Watershed Characteristics and Landscape Factors Influencing Vulnerability and Resilience to Rising Stream Temperatures

Synthesis Element 4: Watershed Characteristics and Landscape Factors Influencing Vulnerability and Resilience to Rising Stream Temperatures

A. Contributors

Nora Jackson, formerly CRC; Judy Okay, Forestry Consultant VDOF; Nancy Roth, Tetra Tech; Sally Claggett, USFS; (Peter Claggett, USGS; *Sequoya Bua-Iam, ORISE Fellow, EPA;* Steve Epting, EPA Healthy Watersheds)*; Renee Thompson, USGS

*advisory capacity

At A Glance Summary

- Land cover and landscape features in a watershed can affect whether stream water temperatures fluctuate at a higher or lower rate than air temperatures. In general, forested landscapes moderate the impact of rising air/stream temperatures, while developed landscapes magnify that impact.

- Recent work has indicated that water temperatures may not be directly correlated with warming air temperatures, and groundwater influence during baseflows can strongly influence stream temperature by mitigating thermal impacts even during droughts (Briggs et al. 2018, Kanno et al. 2014, Snyder et al. 2015, Trumbo et al. 2014).

  Ideal modeling studies would integrate the effects of current and future land use, climate and weather extremes, and hydrologic response. These have not been developed, but are needed to understand best management practices for water temperature and where to apply them.

  Some studies include water temperature as an indicator of watershed health. But even without water temperature per se, future impacts of climate change, temperature, and other stressors depend on the resilience or health of the watershed and beneficial watershed features. Resilient watersheds can recover from temperature increases in their upper reaches.

B. Resources

Resources used in this overview include a mix of studies, models, and previously assessed information focused on hydrologic and anthropogenic activities and stressors that potentially impact water temperature. There is an abundance of literature, geo-spatial tools, and models to help articulate all the influencing landscape factors related to watershed health. To make this task manageable, available resources clearly linked to Chesapeake Bay issues will be used to give a characterization of the landscape and how the characteristics impact stream temperatures.

- The Chesapeake Bay Program's "Chesapeake Healthy Watershed Assessment" (CHWA) Chesapeake Healthy Watersheds Assessment (chesapeakebay.net) is a recent analysis using land cover and an array of watershed characteristics.
- The Maryland Department of Natural Resources publication "Land Use Characteristics of Trout Watersheds in Maryland" provides excellent facts about landscapes and how they matter to water temperature for healthy trout streams.
- An article in Global Change Biology by Maloney et.al., 2020 "Disentangling the Potential Effect of Land Use and Climate Change on Stream Conditions," developed a set of watershed drivers and stressors. These drivers are discussed below.
- Rice and Jastrom's study (2015) of open fields adjacent to streams suggest that a more focused analysis of water temperature trends across the Chesapeake Bay Watershed is needed. They recommend such an analysis should include the physical characteristics that could mitigate or exacerbate water temperature trends. Various landscape features that act as heaters or coolers for water temperature were summarized and correlated in their study.

To identify locations and vulnerabilities of land use change on the landscape, it is helpful to use aerial spectral imagery (high resolution 1m and 10m land use/land cover) and LiDAR to provide status and patterns of landscape change. Land use characteristics and change in the Chesapeake Bay watershed can help contextualize the nature of observed changes in impervious cover, turf grass, forests, wetlands (loss only), tree canopy, and agriculture (2021/2022). In addition, the 2013 and 2017 land use data are being incorporated into the Phase 6 Watershed Model and Chesapeake Healthy Watersheds Assessment (2021 – 2024). Other potentially useful tools are: EPA's Watershed Assessment, Tracking & Environmental Results System (WATERS) and EPA's *Identifying and Protecting Healthy Watersheds: Concepts, Assessments, and Management Approaches* (2012).

C. Approach

This Element 4 Synthesis intends to characterize landscape factors influencing vulnerability and resilience to rising stream temperatures by detailing:

- landscape features that influence increases in stream water temperatures
- landscape features that moderate increases in stream water temperature
- information and tools available for use in watershed management to help with prioritizing vulnerable watersheds
- tools available to prioritize valued working lands for conservation
- landscape features that reduce the vulnerability of watersheds to stream temperature increases

Data that indicate the degree to which the various moderators affect stream temperature on a landscape scale is generally not available. Information to assess watersheds for vulnerability to climate change impacts appears to be adequate as is watershed resilience to withstand disturbances related to climate change.

The framework to be used in this synthesis is constructed from the literature referenced, along with previously applied methodologies and online decision support tools. Landscape factors and land cover characteristics that impact water temperature and related stream health measures are used as organizing features. Where applicable, research needs are identified, and potentially mitigating practices are mentioned.

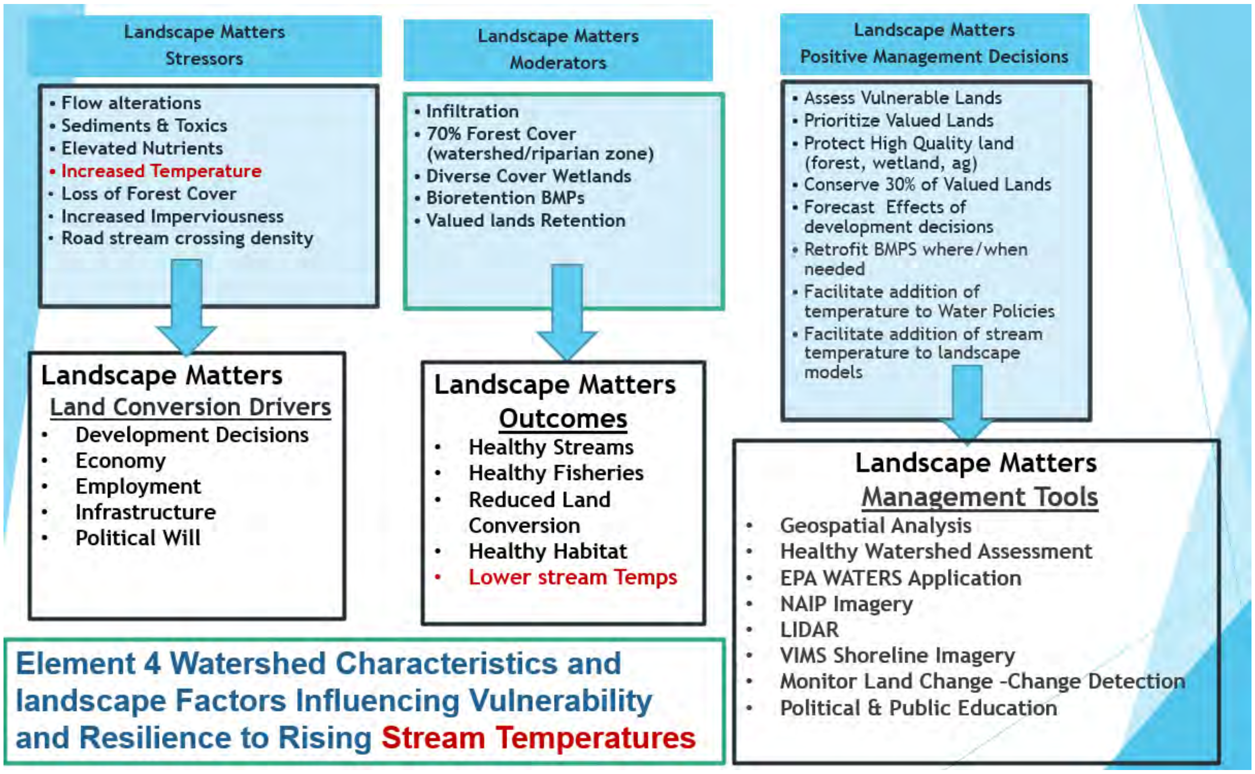
D. Synthesis

Many anthropogenic activities in the watershed have negative implications for the health of the Bay and its tributaries and can affect stream temperature. This synthesis focuses on those landscape variables that are the most influential in either directly or indirectly exacerbating or moderating stream temperature. Indicators such as biological assessments and land cover change have furthered the understanding of the deterioration of stream condition. The approach provided by the Chesapeake Healthy Watershed Assessment (CHWA) includes an index of watershed health that incorporates six key ecological attributes: landscape condition, geomorphology, habitat, water quality, hydrology, and biological condition. (Note: Water temperature is not included in the CHWA at this time but could potentially be added.)

The term ‘best management practices’ is used broadly in this synthesis to include anything people can do that may help to reduce stream temperatures.

Below (Figure 1) is a conceptual model developed for this Element. Each of the boxes contain aspects of landscape factors that influence watershed health. Box 1 Stressors is followed by Stressor Drivers then to Moderators (that reduce or lesson Stressors) and the benefits of the Moderators. The model goes on to feature Positive Management Decisions and tools that can be used to assist in accomplishing Management Decisions.

Figure 1: Watershed Characteristics and Landscape Factors Influencing Vulnerability and Resilience to Rising Stream Temperatures



Land Cover Effects

Land cover has a local effect on watershed health and can have a localized (e.g., shade, air temperatures) and global (e.g., carbon cycle) effect on climate. Land cover can be both moderator (e.g., forests) or stressor (e.g., developed land).

Forest Land

Forest land is decreasing in the watershed. Forests cool the air by evaporating water through their leaves and also moderate the temperature of the ground surface by shading it from direct sunlight. The evaporative cooling effect can decrease local air temperatures by several degrees Fahrenheit. The biomass of large, forested areas has a "specific heat capacity" several times higher than that of soil and air. Specific heat capacity measures the amount of heat stored or released by a unit of mass for one degree change in temperature. Finally, forest soils allow for maximum infiltration to groundwater.

Forest landscapes moderate the effect of increasing air temperature on rivers and streams with relatively narrow streams benefiting the most. Streams draining forested watersheds with major dams warmed more slowly than other watersheds and are likely to become even more important as refugia for cool-water species in a warming world (Rice and Jastram 2015).

Riparian Forest Cover is a best practice

Fisheries are well covered in Synthesis Element 2 however it bears repeating that brook trout is an exceptional indicator of both cool water and forest cover. Cold, high quality water is the basic requirement for the existence of brook trout populations (Kashiwagi, 2018). Increases in water temperatures and the lack of riparian forest cover are implicated for impacts on fisheries (Haley and Auld 2000). Note in Table 1 that the non-native brown trout is neither as sensitive to temperature or expanses of forest cover.

Table 1. *Relationship between trout and forest cover (Kashiwagi, Maryland DNR Fisheries 2018).*

Percent Forest Cover	Trout sp. present
70%	Brook Trout
52%	Brown Trout
46%	No trout

Wetlands

Wetlands with abundant vegetation are another potential cooler of water temperatures. They provide multi-dimensional surface areas for evapotranspiration leading to cooler air temperatures (Stannard et al. 2013 and Sun et al.2015). Wetlands are similar to forest cover in slowing water surges and filtering sediment and nutrients from surface run-off.

Agricultural Land

Agricultural land reduces watershed health, and some features associated with agricultural landscapes are known to impact water temperature. For example, agricultural land use may replace or reduce forested (shaded) riparian zones. Farm ponds are a known source of water warming because they are usually stagnant, shallow, and exposed to solar radiation. The exception are those ponds fed by underground springs which will be cooler than those fed by rainwater and agricultural runoff. Stream diversions such as those associated with irrigated cropland, can mean more solar exposure and therefore more heat. Irrigated cropland also allows for higher rates of evapotranspiration as water is sprayed into the air in summer (Table 2). This act can have a cooling effect on the air, and therefore the nearby water sources, but only so long as the water isn't pooling on fields, where it would be warming.

An agricultural forest buffer --even if narrow -- can have a moderating impact on water temperature. As mentioned above, this is most evident on smaller streams that benefit from the buffer's shade. Other shade-producing vegetation such as emergent wetlands and even lily pads can help reduce solar heating. But overall, agricultural lands are considered to be a source of warming water (Maryland DNR temperature TMDL studies).

Table 2 - Estimated irrigated land and water use in 2010, irrigation water withdrawals. Data adapted from Table 7 in Maupin et al. (2015). Note: These estimates include all irrigated water uses and irrigation systems, not just agricultural crop production, e.g., golf courses, parks, nurseries, cemeteries and other landscape-watering.

	Irrigated land (thousands of acres) by type				Withdrawals (in thousands of acre-feet) by source			
	Sprinkler	Micro-irrigation	Surface-water	Total	Ground-water	Surface-water	Total	Avg rate (acre-feet per acre)
Delaware	132	1.11	0	133	96.5	17.1	114	0.85
Maryland	102	3.43	0	105	59.9	20.9	80.8	0.77
NY	81.1	24.6	2.77	108	33.9	45	78.9	0.73
PA	53	15.1	0	68.1	8.28	22.1	30.4	0.45
VA	102	14.6	0	117	18	50.8	68.8	0.59
WV	2.52	0	1.09	3.61	0.06	0.04	0.1	0.03
Bay state total (whole states, not CBW-only)	473	59	4	535	217	156	373	0.70
National totals	31,600	4,610	26,200	62,400	55,400	73,900	129,000	2.07

Table 2. Estimated irrigated land and water use in 2010.

Developed Land

Developed land is increasing in the watershed. On developed and compacted land, water can be heated by both the surface and the air since it is not able to infiltrate readily. Kaushal (2012) discusses urban stream hierarchy and the loss of headwater streams to the pipes, culverts and ditches of buried streams. This alteration of hydrology (flow) goes hand in hand with increases in the transport of sediment, pollutants, toxics and impervious runoff in general, as well as increased stream temperatures. Kaushal points out that there has been an increasing appreciation for the importance of understanding the structure and function of watersheds and streams from a landscape perspective. As discussed previously, many of the landscape metrics within the CHWA mentioned thus far play a role in exacerbating or mitigating the effects of stream temperature increases and thus represent the stressors that increasing air temperatures of climate change have on streams from the coastal plains to the ridges of the Chesapeake Bay watershed.

The Patapsco River in Baltimore showed the fastest warming of any area of the Bay, implicating urbanization of the watershed and use of the Bay's waters to cool power plants along its shore. A sensitivity analysis showed that out of 14 variables, shade/transmissivity of riparian vegetation, groundwater discharge, and stream width had the greatest influence on stream temperature (LeBlanc et al 1997).

Watershed Assessments

Sets of watershed health and vulnerability metrics, some of which could be represented as stressors have been developed in the Chesapeake Bay Healthy Watershed Assessment (CHWA). Results of exploratory analyses showed that about 10 metrics were consistently selected in model iterations as significant predictors of watershed health, they are displayed in Table 3. These are related to watershed health overall and are not specific to stream temperature.

Model	Pct_Forest_Watershed	Pct_Forest_RZ_Watershed	Pct_Impervious_Watershed	Pct_Impervious_RZ_Watershed	Pct_Wetlands_Watershed	Pct_AgOnHydricSoil_Watershed	Pct_VulernableGeo_Watershed	SPARROW_Total_Nitrogen	SPARROW_Total_Phosphorus	HousingUnit_Density_Watershe_38	Population_Density_Watershed	Mine_Density_Watershed	Managed_Turf_HCZ_Watershed	Pct_Forest_Loss	Pct_Forest_Remaining	Pct_Wetland_Remaining	Road_Stream_Crossing_Density	Dam_Density_Watershed	HabitatConditionIndex_LC	Outlet_Aquatic_ConditionInde_52	Pct_Natural_Land_Watershed
1	Green	Green	Green	Green	Red	Green	Green	Red	Green	Red	Red	Red	Red	Red	Red	Green	Red	Red	Green	Green	Green
2	Green	Green	Green	Green	Red	Green	Red	Red	Green	Red	Red	Red	Red	Red	Red	Green	Red	Red	Green	Green	Green
3	Green	Green	Green	Green	Red	Green	Green	Red	Green	Red	Red	Red	Red	Red	Red	Green	Red	Green	Green	Green	Green
4	Green	Green	Green	Green	Red	Green	Green	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Green	Green	Green
5	Green	Green	Green	Green	Red	Green	Green	Red	Green	Red	Red	Red	Green	Red	Red	Green	Red	Red	Green	Green	Green

Table 3. Chesapeake Healthy Watershed Assessment Metrics- Exploratory analyses: best five model runs showing metrics selected by stepwise linear model. Green box indicates metric provided significant contribution when added to model; red indicates not significant. Note that these are metrics to assess watershed health, not stream temperature per se.

The landscape metrics in the CHWA include percent forest in the catchment, % forest in the riparian zone, Imperviousness in watershed, imperviousness in the riparian zone, agriculture on hydric soil, SPARROW total phosphorus, wetland remaining, habitat condition index, and natural land in the watershed. Noting that some of those metrics that were found to be significant are also correlated, e.g., natural land cover and forest cover. The healthy watershed outcome states that “100% of state-identified currently healthy waters and watersheds remain healthy.” There remains opportunity to better account for rising stream temperature directly through the water quality metrics in the CHWA but also assuring that other landscape factors that influence either negatively or positively stream temperature trends are refined, improved and updated regularly.

Figure 2 identifies the healthy waters, watersheds and protected lands in the Chesapeake Bay watershed. Knowing where the landscape is still intact is of great value in moving toward designating where conservation is needed to protect natural resources and their ecological services.

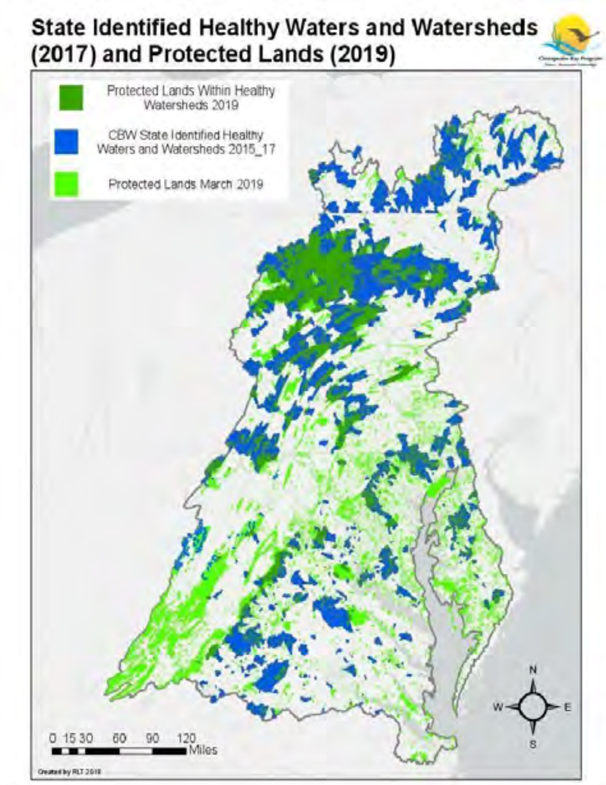


Figure 2. *State-Identified Protected Healthy Watersheds, Chesapeake Bay Program, 2019*

The degree of impact from climate change depends on the vulnerability and resilience of ecosystems and the ability to adapt to the changes. In a healthy watershed, change should not cause a permanent impact, because riparian areas and floodplains help to absorb some of the disturbance. For the purposes of the CHWA, resilience is defined by the landscape attributes and watershed characteristics that allow for high value habitat and healthy waters to sustain despite those potential stressors. CHWA includes a metric called vulnerable geology and includes areas vulnerable to surface or groundwater degradation. Values of “carbonate” and “coarse coastal plain” are considered the vulnerable areas.

The Maryland Healthy Watershed Assessment (MDHWA) pilot project has compiled candidate metrics to be tested for effectiveness (the strength of the relationship between the metric and stream response) to track watershed health in a repeatable manner (Tetra Tech, Inc., 2021). A more final listing of the key metrics --particularly stream temperature increases and moderations-- are expected in March 2022.

Like the Maryland project described above, Rice and Jastrom (2015) focused on water temperature and landscape relationships concluding that continued warming of contributing streams to Chesapeake Bay will likely result in shifts in the distribution of aquatic biota. Nelson and Palmer (2007) studied stream temperature surges in conjunction with urbanization and climate change. They found that average stream temperature increased as deforestation increased in a watershed. This finding accentuates the forest cover stream temperature relationship. This study also showed that high runoff events associated with localized rain storms caused surges in stream temperatures averaging 3.5 degrees.

Maloney et al. (2020) also produced a set of factors that influence watershed health. The study primarily used landscape elevation, stream size (smaller order streams), macro-invertebrate data (IBI, index of biotic integrity) seasonal average temperatures and land cover changes. Where land cover changes were lower, forest cover increased, and fewer streams were predicted to fall to degraded conditions (poor IBI scores). This study also presents the theory that smaller streams in valley settings are more vulnerable to degradation than those streams in the ridge elevations of the watershed. This is premised on valleys being areas of higher levels of development because of level topography making development easier.

Elements 7 & 8 Synthesis covers the many benefits forests cover and riparian buffers provide for watersheds. With advances in high resolution imagery, hydrography, modeling, monitoring and analysis, there is more understanding of how landscapes can affect stream temperature. Synthesis Element 5 has in-depth information regarding the past and current Bay conditions. This gives a good starting point for reducing impacts stressing natural resources.

Moderators and Drivers of Stressors

It is not surprising that some of the same stressors related to watershed health are also implicated in stream temperature rise. Likewise, some of the outcomes sought by the 2014 Chesapeake Bay Agreement would also benefit stream temperatures, specifically: cross-outcome goals for forestry, brook trout, land conservation, healthy watersheds, stream health, water quality, etc. Table 4 summarizes key metrics included in the Healthy Watersheds Assessment framework and how they are related to stream temperature.

Table 4. *Key metrics and relationship to stream temperature (Maryland Healthy Watershed Assessment).*

HWA Sub-Indices	Metrics	Influence on Stream Temperature
Landscape Condition	% Natural Land Cover in Watershed % Forest in Riparian Zone in Watershed % Imperviousness in Watershed	Decrease leads to elevated stream temp Decrease leads to elevated stream temp Increase leads to elevated stream temp
Hydrology	% Forest in Watershed	Decrease leads to elevated stream temp High density and low area forest cover leads to increase in stream temp

	Density Road-Stream Crossings in Watershed % Wetlands in Watershed Flow alteration score	High quality wetlands help stabilize stream temp Diverse wetlands are air temperature moderators Water withdrawal promotes high water temps
Geomorphology	Dam Density Road Density in Riparian Zone, in Watershed % Impervious in Riparian Zone in Watershed	Increase in dam density can lead to changes in land cover that may affect stream temperature, warmer temperatures are associated in closer proximity to dams (Zaidel, P., Roy A., 2021) More roads are indicators of more pavement and increased air temperatures More imperviousness in the riparian zone indicates less forest cover and warmer air temperatures.
Habitat	Nature's Network Conservation Habitats in Catchment Forest Habitat (Forest interior) MBSS Stronghold Watersheds Maryland Biodiversity Conservation Network (Bio-Net) MBSS Physical Habitat Indicator	Healthier watershed Cooler healthier environment Higher IBI scores indicate healthier watersheds Prioritizes areas for terrestrial and freshwater biodiversity conservation (sensitive habitats) Indicator of sensitive species habitat -potential conservation areas
Water Quality	Stream impairments from MD Integrated Report data Conductivity USGS SPARROW sector specific loads (manure, fertilizer, urban wastewater, atmospheric, septic) for TN, TP, sed (incremental loads) Stream Temperature (future metric for consideration 2022)	Combined report of 305(b) and 303(d) streams not meeting TMDL standard Conductivity indicates the presence of various ions related to many possible pollutants or no pollutants. Pollutants lead to higher water temperatures.(Moore et al., 2020) Can be moderated by vegetative land cover

Land Use Change	% Increase in Development in Catchment	Development can be a surrogate for imperviousness and leads to higher water temperatures.
	Recent Forest Loss in Watershed	This factor is reflected by higher air and related water temperatures
	% Protected Lands in Watershed	Increase in protected acres has potential to lower developed acres and increase more favorable land cover for moderating stream temps

The percent increase in development, the loss of forest cover, increases in imperviousness are indicated as stressors in Table 4. All of these have the common characteristics of influencing both the rate of surface runoff and the time it takes for runoff to infiltrate into local soils. One of the most important moderators of water temperature is infiltration. Water needs to get from the landscape into the streams in the most natural way possible, allowing the infiltrated water to cool. Table 5 has the infiltration rates for common landscape cover/surfaces.

In a study by Bharati et al. (2002) an established riparian buffer had infiltration rates five times that of fields or pastureland. As noted in studies cited in this synthesis, loss of forest cover is a negative factor contributing to ambient temperature increases. Those natural landscapes and best management practices that have higher infiltration rates allow for increases in groundwater recharge. Groundwater recharge is a cooling element for stream water (Murray 2006).

Table 5. Infiltration rates for common landscape cover/surfaces.

Landscape Cover	**Infiltration rate inches/hour**
Forest (pine needle cover)	15.92
Grass (avg. flat lawn)	0.28-0.88
Bioretention (Virginia DOT manual)	0.52-8.27
Rain Garden (NOAA Citizen's Guide)	0.50-2.00

This table was compiled from various guides, papers, and websites (Okay 2021)

Geospatial analysis tools can be used to forecast development decisions which could impact water temperature. StreamCat (Catchments) is an extensive database of landscape metrics for ~2.65 million stream segments within the continental United States and one of the only assessments that includes stream temperature.

Next Steps

1. Work to integrate stream temperature data and other landscape stressor and moderator information into assessments and priority mapping and analysis
    - Add stream temperature to Water Quality metrics of the Chesapeake Healthy Watersheds Assessment

    - Investigate opportunities to better integrate stream temperature considerations into Chesapeake Conservation Partnership priority conservation atlas mapping efforts.
    - Investigate opportunities to connect watershed health, vital lands and habitat protection to stream temperature and water quality goals
2. Work to decrease stressors
    - Emphasize the need to maintain natural landscapes (especially forests and wetlands) and healthy watersheds
    - Continue to improve policies that keep these land covers protective of water temperature
    - Continue to promote permanent protection of these lands

3. Employ practices that modify stream temperatures
    - Promote best practices for cooling streams as listed in Table 4. (Note that Synthesis for Element 7/8 goes into greater depth on best management practices).

E. Evaluation Element 4 Synthesis

In considering research that would be used in this Synthesis the overarching qualifications were: The research originated in, is related to, or can be applied to the Chesapeake Bay Watershed. To characterize the landscape/land use issues that relate to disturbances or stress to watersheds, a suite of assessment tools was highlighted and the metrics used for assessment are described and represented in tabular form. Stressors common to the assessment tool metrics and supported by the science of the research papers are:

- Land use changes/conversions (especially loss of forest cover, increase of impervious surface)
- alteration of stream flow
- increased sediment
- toxics
- pollutants and nutrients.

The objective is to show that these watershed stressors are causative factors to increased stream water temperatures.

- Nelson and Palmer (2007) related a stream temperature increase of 3.5 degrees C in response to high surface runoff events and deforestation.
- Maloney et.al (2020) demonstrated that with increased impervious cover stream conditions declined and with increased tree canopy conditions improved.
- Kaushal (2012) had findings that agree with those of Maloney.
- Kawishagi (2018) linked percent forest cover to the presence of trout in Maryland cold water streams.
- Goetz (2003) showed a positive relationship between forest buffers and stream health.

- Stannard et al. (2013) and Sun et al.(2015) suggested wetland restoration as a tool to reduce air temperature increases stemming from climate change.

Alteration of stream flow and stream temperature fluctuations were addressed by linking infiltration of surface water into the soil to recharge groundwater. The discharge of the water from groundwater can have a cooling effect that stabilizes stream temperature, and it also stabilizes seasonal flows, depending on other key landscape factors. These are important factors for cool water fisheries. The relationship of infiltration with various types of land cover is highlighted. Forests have the highest infiltration rates. As a land cover they facilitate infiltration to groundwater better than other land cover. In contrast, pavement has the highest run-off coefficient limiting infiltration and groundwater recharge. How quickly water runs off determines the concentration time which allows the water to infiltrate into the soil and recharge groundwater. The infiltration rates are lower for the more impervious cover types and higher for the more porous cover types.

The presentation is strong on tools, moderate on scientific support to identify stressors and moderators. Data that indicate the degree to which the various moderators affect stream temperature on a landscape scale is generally not yet available. Watershed assessment, vital lands and habitat priority mapping and other related living resource mapping and assessments should be evaluated to include more robust information on stream temperature as it is related to watershed health, water quality, landscape resilience, and high value habitat. Information to assess watersheds for vulnerability to climate change impacts appears to be adequate as is watershed resilience to withstand disturbances related to climate change.

References:

Bharati, L., Lee, KH., Isenhart, T. *et al.* Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. *Agroforestry Systems* **56,** 249–257 (2002). https://doi.org/10.1023/A:1021344807285

Briggs, M. A., Johnson, Z. C., Snyder, C. D., Hitt, N. P., Kurylyk, B. L., Lautz, L., Irvine, D. J., Hurley, S. T., & Lane, J. W. (2018). Inferring watershed hydraulics and cold-water habitat persistence using multi-year air and stream temperature signals. Science of The Total Environment, 636, 1117–1127. https://doi.org/10.1016/j.scitotenv.2018.04.344

Chesapeake Healthy Watersheds Assessment: Assessing the Health and Vulnerability of Healthy Watersheds within the Chesapeake Bay Watershed. (2020). Tetra Tech, Inc. https://www.chesapeakebay.net/channel_files/26540/chesapeake_healthy_watersheds_assessment_report.pdf

Goetz, S. Jantz, C. Prince, S. (2003). Integrated Analysis of Ecosystem Interactions with Land Use Change: Chesapeake Bay Watershed. *Geophysical Monograph Series 153.*

Haley, D. and Auld, H. Integration of Climate Change into Watershed Management. This paper was presented at the Ontario Water Conference, *Challenges and Solutions*, which took place in Richmond Hill, April 26-27 of 2000.

Kashawagi, M. (2020). Land Use Characteristics of Trout Streams in Maryland. DNR Fisheries website: *dnr.maryland.gov.>fisheries>Documents.*

Kanno, Y. Vokoun, J.C. and Letcher, B.H. (2014). Paired Stream-air Temperature Measurements Revel Fine-Scale Thermal Heterogeneity Within Headwater Brook Trout Stream Networks. River Res. Applic., 30: 745-755. https://doi.org/10.1002/rra.2677

Kaushal, S.S., Belt, K.T. The urban watershed continuum: evolving spatial and temporal dimensions. *Urban Ecosyst* **15,** 409–435 (2012). https://doi.org/10.1007/s11252-012-0226-7

Kennedy, V. Twilley, R. Kleypas, J. Cowan Jr., J. Hare, S. (2002). Global Climate Change Coastal and marine ecosystems: Potential Effects on U.S. Resources & Global Climate Change. *Prepared for the Pew Center.*

LeBlanc, R. T., Brown, R. D., & FitzGibbon, J. E. (1997). Modeling the Effects of Land Use Change on the Water Temperature in Unregulated Urban Streams. Journal of Environmental Management, 49(4), 445–469. https://doi.org/10.1006/jema.1996.0106

Maloney, KO, Krause, KP, Buchanan, C, et al. Disentangling the potential effects of land-use and climate change on stream conditions. *Glob Change Biol*. 2020; **26**: 2251– 2269. https://doi.org/10.1111/gcb.14961

Maryland Healthy Watersheds Assessment: Strategy for Development of the Maryland Healthy Watershed Assessment, *Prepared by Tetra Tech, Inc*., Owings Mills, MD , REVISED July 31, 2021 accessible via email rthompson@chesapeakebay.net

Moore, J., Fanelli, R. M., & Sekellick, A. J. (2020). High-Frequency Data Reveal Deicing Salts Drive Elevated Specific Conductance and Chloride along with Pervasive and Frequent Exceedances of the U.S. Environmental Protection Agency Aquatic Life Criteria for Chloride in Urban Streams. *Environmental Science & Technology, 54*(2), 778-789.

Murray, Brad et.al. (2006). Valuation of Groundwater Dependent Ecosystems: A Functional Methodology Incorporating Ecosystem Services. Australian Journal of Botany (54) 221-229.

Nelson, K.C. and Palmer, M.A. (2007), Stream Temperature Surges Under Urbanization and Climate Change: Data, Models, and Responses. J*AWRA Journal of the American Water Resources Association,* **43**: 440-452. https://doi.org/10.1111/j.1752-1688.2007.00034.x

Rice, K.C., Jastram, J.D. Rising air and stream-water temperatures in Chesapeake Bay region, USA. Climatic Change 128, 127–138 (2015). https://doi.org/10.1007/s10584-014-1295-9

Snyder, C.D., Hitt, N.P. and Young, J.A. (2015), Accounting for groundwater in stream fish thermal habitat responses to climate change. Ecological Applications, 25: 1397-1419. https://doi.org/10.1890/14-1354.1

Stannard, D.I., Gannett, M.W., Polette, D.J., Cameron, J.M., Waibel, M.S., and Spears, J.M., (2013). Evapotranspiration from marsh and open-water sites at Upper Klamath Lake, Oregon, 2008–2010: U.S. Geological Survey Scientific Investigations Report 2013–5014, 66 p.

Sun, Z., Sun, W., Tong, C., Zeng, C., Yu, X., & Mou, X. (2015). China's coastal wetlands: Conservation history, implementation efforts, existing issues and strategies for future improvement. Environment International, 79. https://doi.org/10.1016/j.envint.2015.02.017

Trumbo, B. A. Nislow, K. H. Stallings, J. Hudy, M. Smith, E. P. Kim, D. Wiggins, B & Dolloff, C.A. (2014). Ranking Site Vulnerability to Increasing Temperatures in Southern Appalachian Brook Trout Streams in Virginia: An Exposure-Sensitivity Approach, Transactions of the American Fisheries Society, 143:1, 173-187, DOI: 10.1080/00028487.2013.835282

U.S. Environmental Protection Agency. (n.d.). EPA. Retrieved October 5, 2021, from https://www.epa.gov/waterdata/waters-watershed-assessment-tracking-environmental-results-system.

U.S. Environmental Protection Agency. (2012). Identifying and Protecting Healthy Watersheds: Concepts, Assessments, and Management Approaches (EPA-841-B-11-002). Washington, DC: U.S. Environmental Protection Agency, Office of Water, Office of Wetlands, Oceans and Watersheds. Retrieved from https://www.epa.gov/sites/production/files/2015-10/documents/hwiwatersheds-complete.pdf. Accessed on 3/1/2019.

Zaidel, P. A., Roy, A. H., Houle, K. M., Lambert, B., Letcher, B. H., Nislow, K. H., & Smith, C. (2021). Impacts of small dams on stream temperature. Ecological Indicators, 120, 106878. https://doi.org/10.1016/j.ecolind.2020.106878

Appendix I
Synthesis Element 5: Past, Current and Projected Changes in Watershed and Tidal Water Temperatures and Implications for Ecosystem Processes Influencing Stream, River and Estuarine Health

Synthesis Element 5: Past, Current and Projected Changes in Watershed and Tidal Water Temperatures and Implications for Ecosystem Processes Influencing Stream, River and Estuarine Health

At a Glance Summary

- Chesapeake Bay watershed air temperatures and stream-water temperatures have been rising since the 1960s and at higher rates during the 1985-2010 period compared with the 1961-1985 period.
- Stream-water temperatures have been rising fasters than air temperatures across the Chesapeake Bay watershed, indicating land use-based factors are also influencing stream-water temperatures.
- Chesapeake Bay tidal water temperatures have been increasing over the past three decades, driven largely by atmospheric forcings and the warming ocean boundary.
- These increasing watershed and tidal water temperatures have significant implications for aquatic living resources and the underlying biological and physical processes which directly influence habitat suitability.

A. Contributors

Rich Batiuk, CoastWise Partners; Nora Jackson, Chesapeake Research Consortium/Chesapeake Bay Program Office; John Clune, United States Geological Survey; Kyle Hinson, Virginia Institute of Marine Science; Renee Karrh, Maryland Department of Natural Resources; Mike Lane, Old Dominion University; Rebecca Murphy, University of Maryland Center for Environmental Science/Chesapeake Bay Program Office; and Roger Stewart, Virginia Department of Environmental Quality.

B. Resources

Published papers cited as references; Chesapeake Bay water quality monitoring network’s long term trend analyses generated by Rebecca Murphy, Renee Karrh, and Mike Lane; U.S. Environmental Protection Agency Climate Change Indicator development documentation; Pennsylvania Report on Climate Impacts; and interviews with recognized regional scientists and data analysts.

C. Approach

Synthesized evidence for long term changes in watershed and tidal Bay water temperatures, then engaged researchers and statistical analysts currently involved in in-depth analysis and evaluation of both the trends and the likely underlining causes behind the observed trends and finished with accounting for the implications for the watershed and estuarine ecosystem.

D. Synthesis

Watershed and Tidal Bay Water Temperature Trends

Watershed and tidal Bay water temperatures are rising and have been for the past several decades. Preston (2004) reported an average Bay water temperature increase of ~0.8-1.1°C from 1949-2002 as derived from direct observations and satellite measurements. Ding and Elmore (2015) found increases in Chesapeake Bay surface water temperature of ~0.4-2°C from 1984-2010, also based on direct observations and satellite measurements. U.S. Geological Survey trend analysts reported that average non-tidal stream temperatures increased 2.52 °F from 1960 to 2010, while air temperatures increased 1.99 °F (Rice and Jastram 2015).

Non-Tidal Water Temperature Trends

Key takeaways from trend analysis of monthly mean air temperature at 85 sites and instantaneous stream-water temperature at 129 sites within or near the Chesapeake Bay watershed from 1960 to 2010 (Rice and Jastram 2015) (Figure V-4) include:

- Analysis of both air and stream-water temperatures for two periods, 1961–1985 and 1985–2010, relative to the climate normal period of 1971–2000, indicate that the 1985-2010 period was statistically significantly warmer than the 1961-1985 period for both mean air temperature and stream-water temperature;
- Across the Chesapeake Bay watershed and the surrounding region, statistically significant temporal trends of 0.023 °C per year for air temperature and 0.028 °C per year for stream-water temperature were determined;
- From 1960 through 2010, water temperature increased significantly at 53 of 129 stations analyzed in the region;
- Stream-water temperature decreased significantly at 7 of those 129 stations over the same period;
- In areas where major dams were and the land cover was principally deciduous forest, stream-water temperatures were increasing slower than air temperatures, whereas agriculture-dominated regions in the absence of major dams were correlated with stream-water increasing faster than air temperatures;
- Increasing stream-water temperature trends are detected despite increasing trends in streamflow in the northern Chesapeake Bay watershed and surrounding region; and
- Increases in water temperature occurred at the greatest rates in the southern Chesapeake Bay watershed and surrounding region.

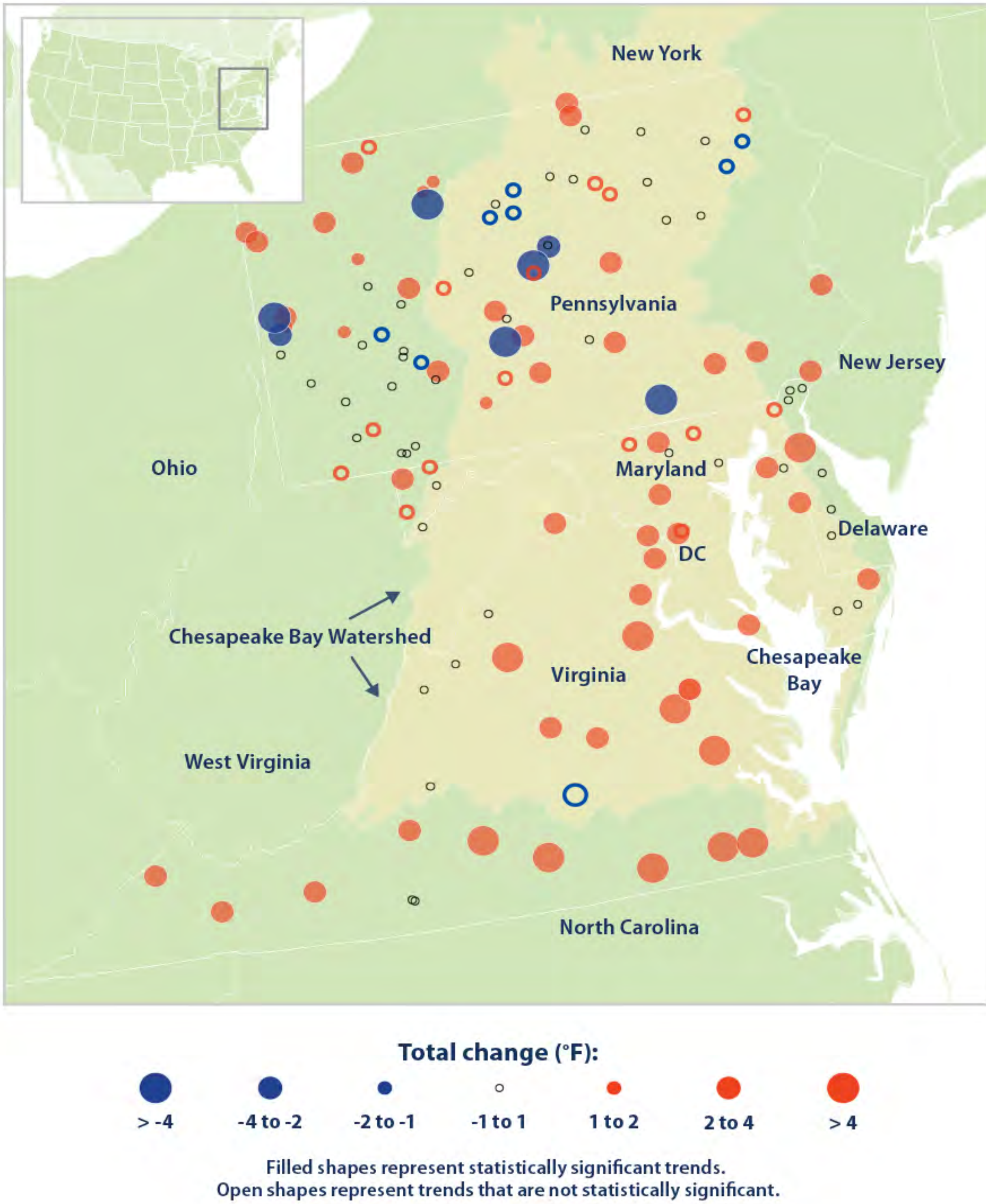


Figure V-1. Changes in stream water temperatures in the Chesapeake Bay Region, 1960–2010.

Source: Rice and Jastram 2015

The map in Figure V-1 shows the change in water temperature at 129 stream gauges across the Chesapeake Bay region from 1960 to 2010. Red circles show locations where temperatures have increased; blue circles show locations where temperatures have decreased (Rice and Jastram 2015). Filled circles represent sites where the change was statistically significant based on the U.S. EPA Climate Indicator[1].

Water temperature in streams can be affected by factors other than climate, including industrial thermal discharges, hydrologic alteration (for example, channelization, piping, and impoundment), land cover, location, and topography. A more detailed analysis of this data set found that water temperature tends to increase more quickly than air temperature in agricultural areas without major dams, but more slowly at forested sites and in areas influenced by dams (Rice and Jastram, 2015). For this indicator, water temperature measurements from all available stream gages with appropriate records within the study area were used, as described in Rice and Jastram (2015), regardless of potential influences from anthropogenic disturbances.

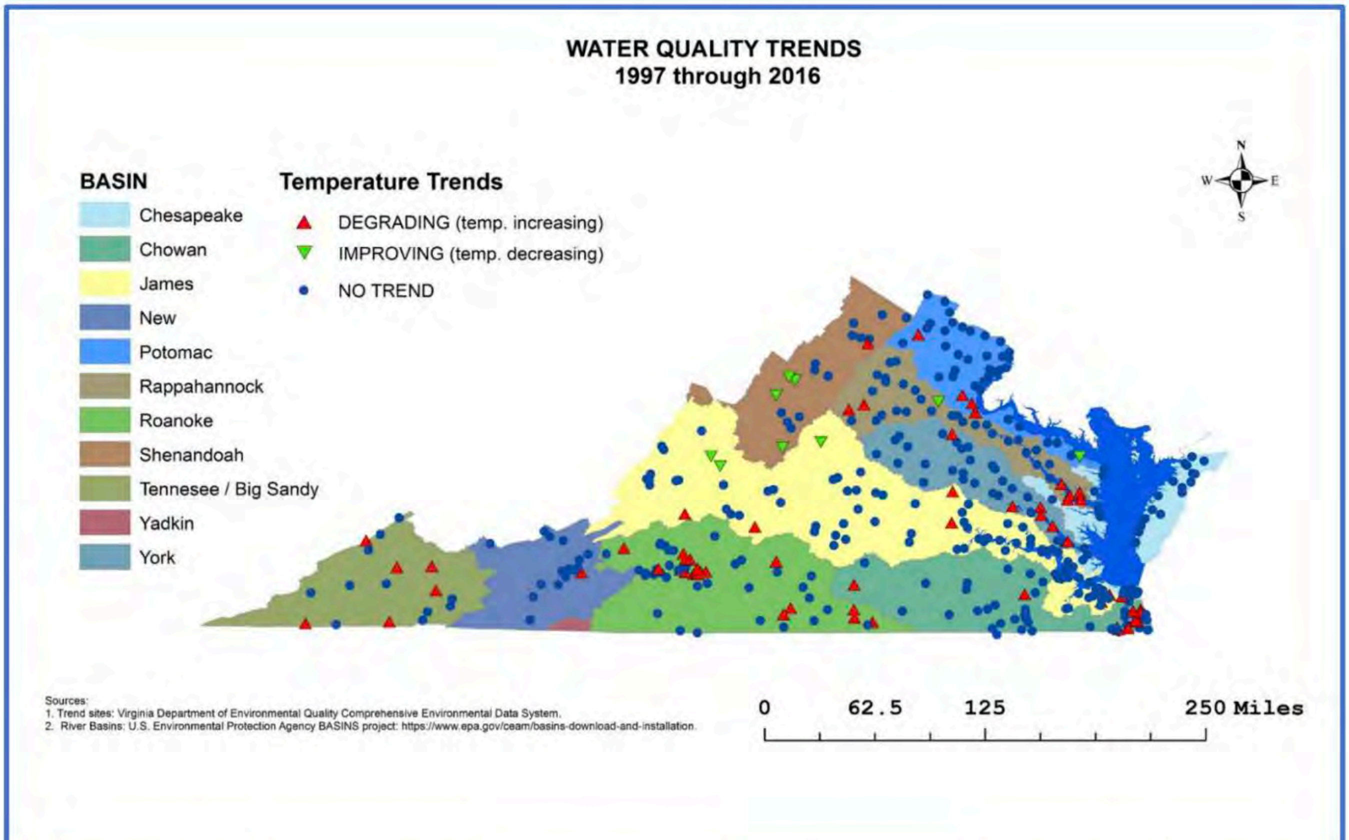
A comparison, using the Rank-Sum test (Helsel and Hirsch, 2002), of relatively undisturbed reference stations (n = 35), as determined by Falcone (2011), with all other stations (n = 94) in the dataset demonstrated no significant difference (alpha = 0.05) in trends between the two groups of stations. Trends were determined using ordinary least-squares linear regression of sites-specific monthly water temperature anomalies, as described by Rice and Jastram (2015). The Cochrane-Orcutt method (Cochrane and Orcutt, 1949) was used to remove the effect of serial correlation, thus allowing determination of the statistical significance of water temperature trends at individual stations. Of the 129 stations analyzed, 60 (47 percent) had trends that were significant to a 95-percent level ($p \leq 0.05$), including 53 stations with temperature increases and seven with decreases.

Sources of variability include localized factors such as topography, geology, elevation, and natural land cover within individual watersheds. Variability between individual temperature measurements could result from variations in weather—for example, if a recent storm led to an increase in streamflow. Additionally, some sites may be more affected by direct human influences (such as land-cover and land use change or hydrologic modification) than others and does not include any sites that are affected by tides.

The Virginia Department of Environmental Quality operates a network of 410 permanent trend stations where monthly or bimonthly data are collected for a variety of key water quality parameters. These fixed stations are located in areas of special interest including those near the mouths of our major rivers, along the fall line, near flow gaging stations, at designated non-tidal stations monitored to evaluate how rivers affect the Chesapeake Bay. In the 2018 Integrated Report on Water Quality Trends in Virginia from 1997-2016, water temperature was included in the trend analysis as a water quality indicator variable (Figure V-2) (Steward 2018). Temperature has an influence on regulating respiration rates, spawning, and the maximum concentration of dissolved oxygen in solution with the ambient

1 https://www.epa.gov/climate-indicators/climate-change-indicators-stream-temperature.

water (increasing temperature reduces dissolved oxygen saturation in water and, therefore, may limit respiration). In addition, animals and plants under thermal stress from high-water temperatures are at increased risk of adverse effects from other pollutants. Temperature standards exist for “the propagation and growth of a balanced indigenous population of aquatic life” as described in the Clean Water Act (33 U.S.C. §1251 et seq; this is, more correctly, a balanced and indigenous community of aquatic life). Pollution events that cause harm to aquatic communities via water cooling are extremely rare in VA, and not known to exist at the stations in the trend network. Therefore, increasing trends in water temperature are considered degradation, and decreases in temperature are considered improvements (Stewart 2018).



SURFACE WATER TEMPERATURE	% NO TREND	% IMPROVING	% DEGRADING	STATIONS	N
	82	2	15	410	64,189

Figure V-2. Surface Water Temperature Trends in Virginia 1977-2016

Source: Steward 2018.

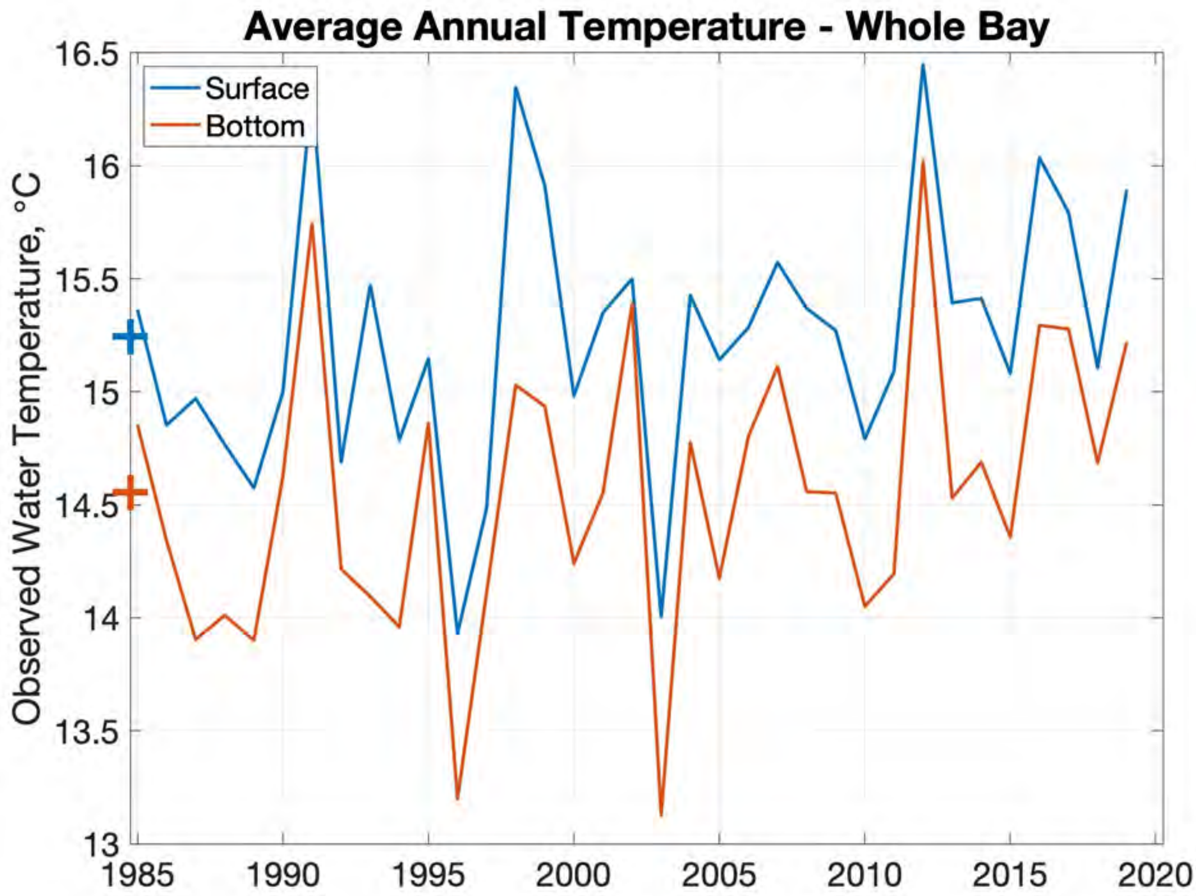


Figure V-3. Observed annual averaged surface and bottom water temperatures across Chesapeake Bay from 1985 through 2020.

Source: Hinson et al. 2021

Tidal Bay Water Temperature Trends

Using estimates of changes from downscaled global climate models (GCMs) and the Chesapeake Bay Program Partnership's modeling framework, Tian et al. (2021) documented and projected changes in Chesapeake Bay water temperatures of 0.85-0.9°C from 1995-2025. When Hinson et al. (2021) used a combination of observations and model outputs to report that throughout Chesapeake Bay's mainstem, similar warming rates were found at the surface and bottom between the late 1980s and late 2010s of 0.02 °C per year, with elevated summer rates (0.04 °C per year) and lower rates of winter warming (0.01 °C per year) (Figure V-3). These annual rates yielded an annual average Bay-wide warming of ~0.7°C throughout the Chesapeake Bay's water column over the past 30-year period, with a 1.0 °C increase during the summertime and a 0.3°C during the winter months over the same three-decade period (Hinson et al. 2021).

Recent work by Murphy and colleagues (personal communication), using generalized additive model approach to evaluating water quality as described in Murphy et al. 2019, yielded the 1985-2019 estimated changes in tidal water bottom and surface temperatures seen in Figures V-4 and V-5, respectively.

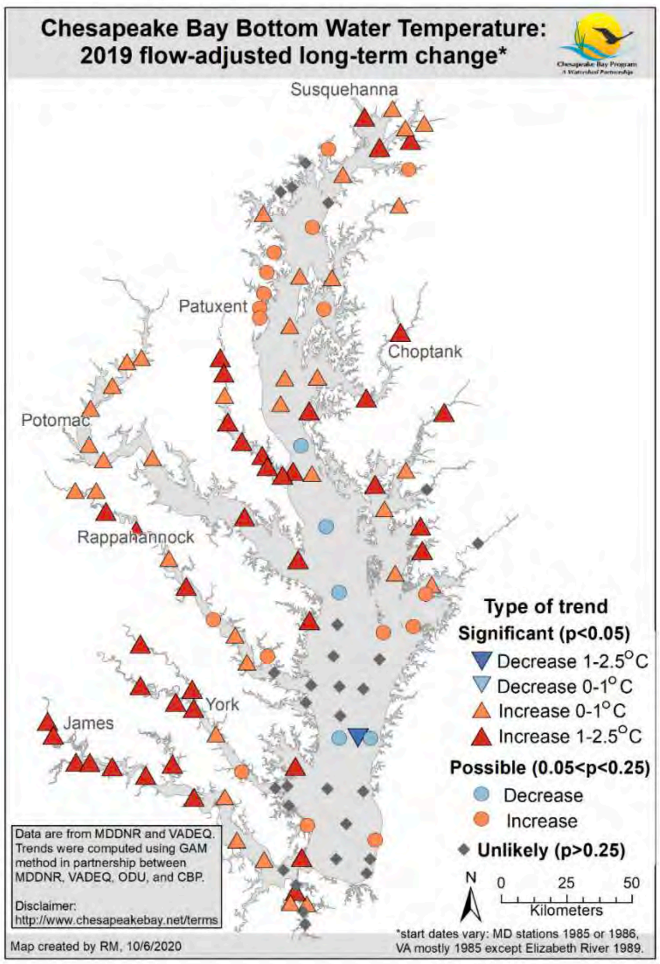


Figure V-4. Left. Long term flow-adjusted trends in surface water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019.

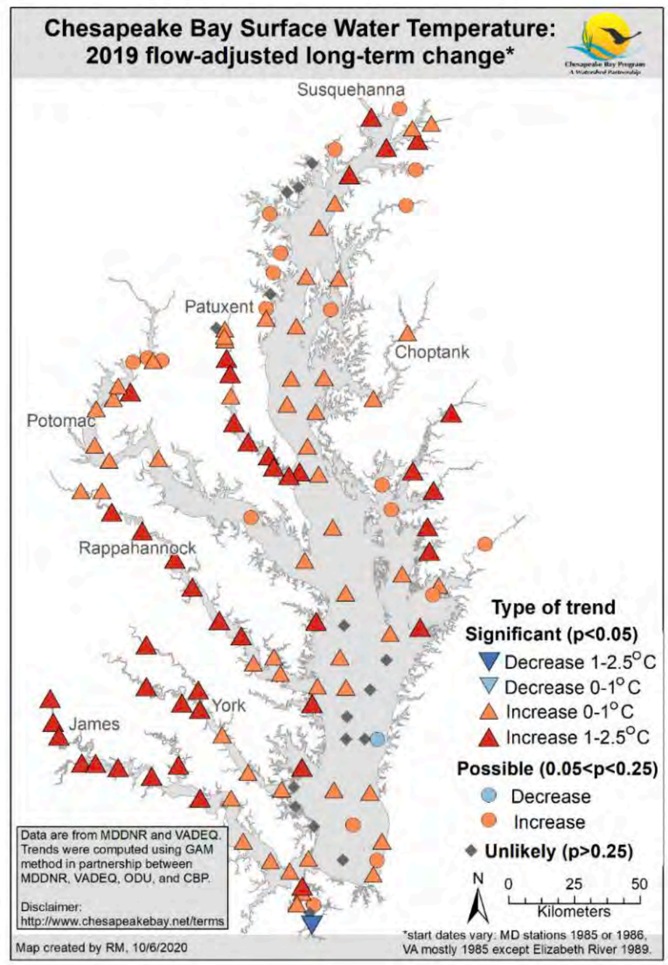


Figure V-5. Right. Long term flow-adjusted trends in bottom water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019.

Driving Forces Behind Warming of Chesapeake Bay Tidal Waters

Hinson et al. (2021) have identified four principal mechanisms responsible for the observed increasing temperatures of Chesapeake Bay's tidal waters, listed here in the order of their relative influence: atmospheric forcings, warming ocean boundary, sea level rise and increasing river temperatures (Figure V-6).

Hinson et al. 2021 utilized "the extensive observational network of in situ data along with a watershed-estuarine modeling system forced by realistic atmospheric and oceanic inputs to quantify and better understand the causes of warming in the Chesapeake Bay. Using this approach, a more robust estimate of the recent observed temperature trends and the causality of said trends can be more precisely determined."

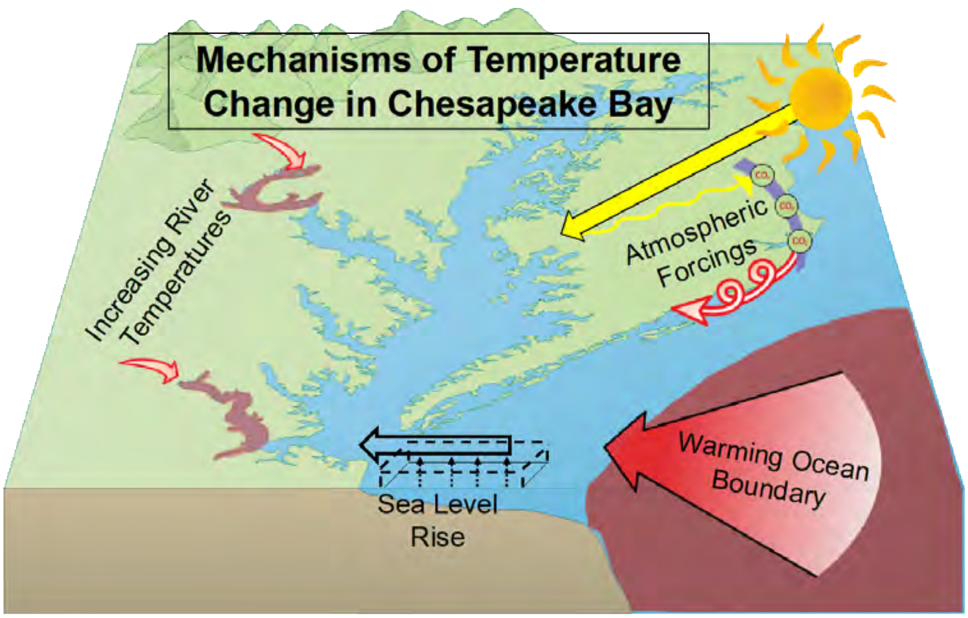


Figure V-6. Illustration of the four major major mechanisms driving changes in water temperature throughout the Chesapeake Bay's mainstem, tidal tributaries and embayments.

Source: Hinson et al. 2021

Temperature changes were largely very similar at the Bay's and tidal tributaries' surface and bottom of the water column (Hinson et al. 2021) (Figure V-7). Some regional differences in temperature changes were reported, with higher temperature changes estimated for the Susquehanna Flats and adjoining upper Bay mainstem, the lower Bay and mouth of the Bay, and the tidal fresh reaches of the major tidal tributaries (Figure V-8). There is evidence supporting river temperature influences in the upper tidal fresh reach of the major tidal tributaries and the upper Chesapeake Bay—Susquehanna Flats and the upper Bay mainstem reach down to about Back River on the western shore (see Figure V-7).

Sea level rise is estimated to slightly cool Bay mainstem water column temperatures from April through September, and result in the warming of bottom Bay mainstem waters in the winter months (November through February) (Figure V-10) (Hinson et al. 2021). Increasing ocean temperatures are estimated to contribute significantly to the summer warming of the Bay water column temperatures between June and October, with a small effect on water column temperature for the remaining months of the year (Figure V-10). Atmospheric forcings are estimated to play biggest role in driving increasing water column temperatures throughout the Bay's tidal waters, but the effects on water temperatures are lessened during summer months of July through September and contribute to a cooling of Bay water temperatures during December (Figure V-10).

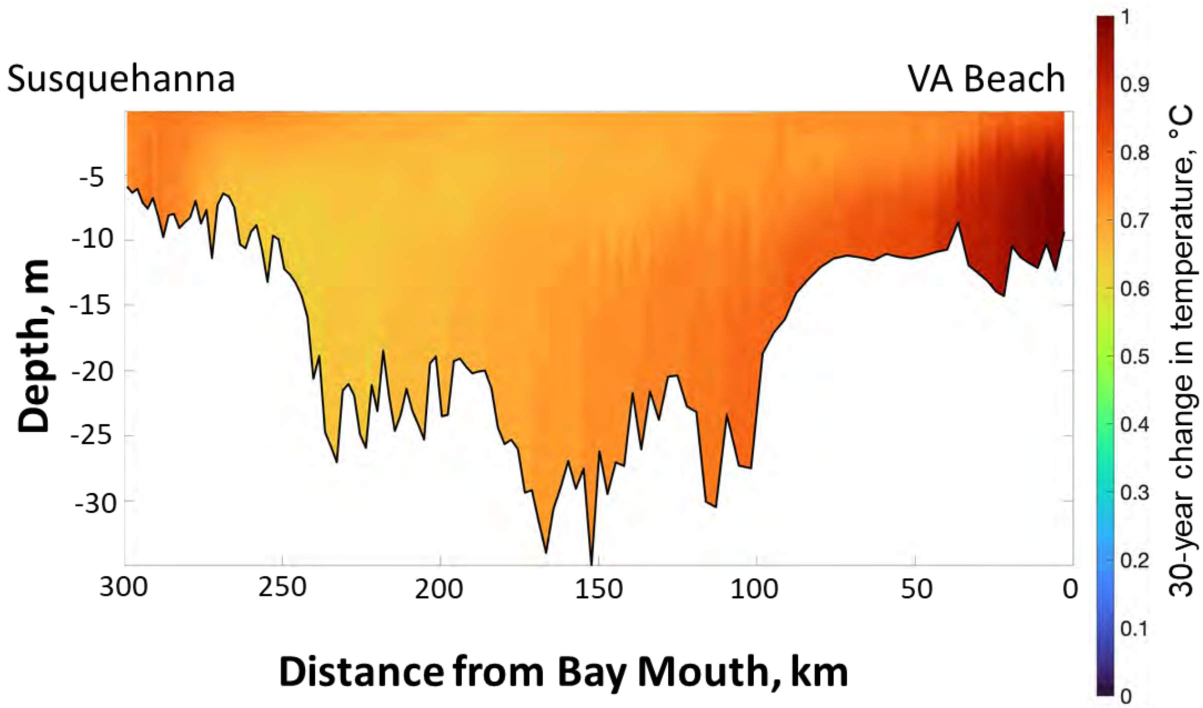


Figure V-7. Two-dimensional depth profile of the 30-year change in water column temperature along the Chesapeake Bay mainstem.

Source: Hinson et al. 2021

There is substantial variation in the estimated water column temperature changes over the past 30 years between months, with generally more warming of water temperatures from May-October than November-April (Figure V-9). The observed increasing river temperatures are estimated produce very limited warming of water column temperatures in the Bay's mainstem (Hinson et al. 2021) (Figure V-10).

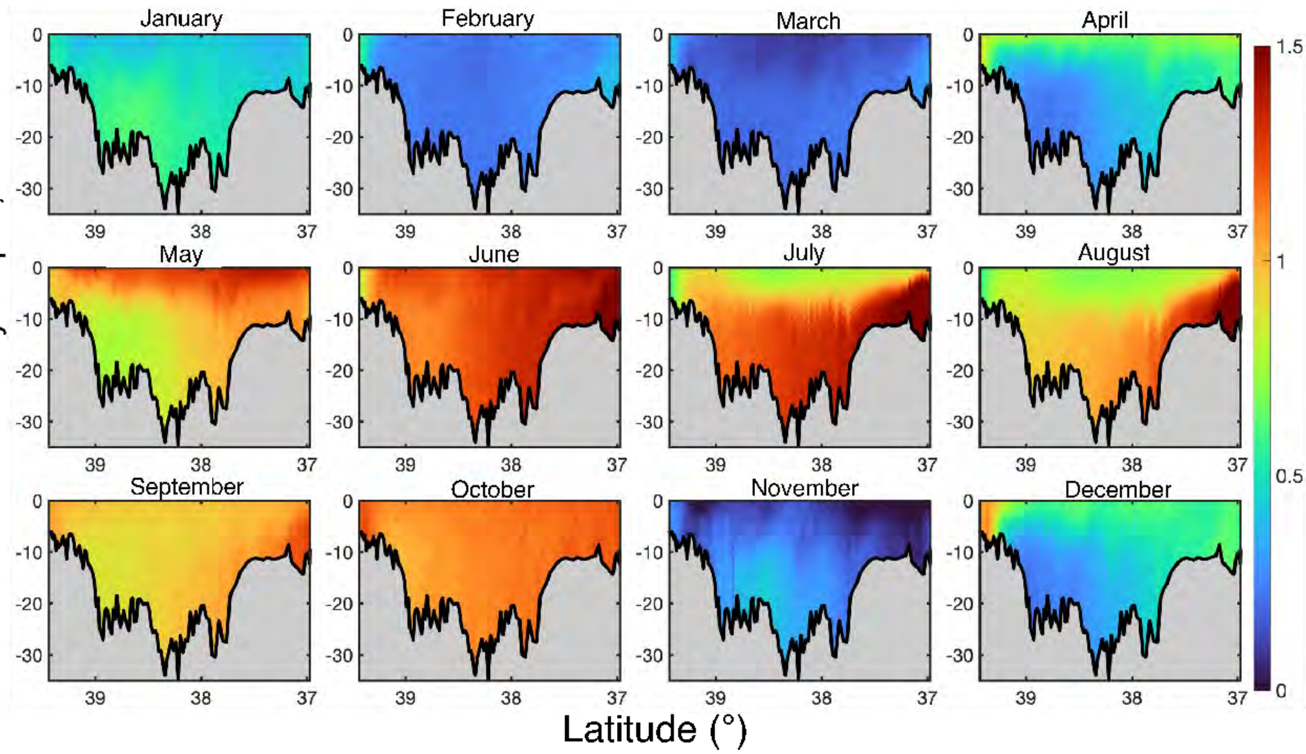


Figure V-8. The 30-year change in observed water temperatures at the surface and bottom across Chesapeake Bay.

Source: Hinson et al. 2021

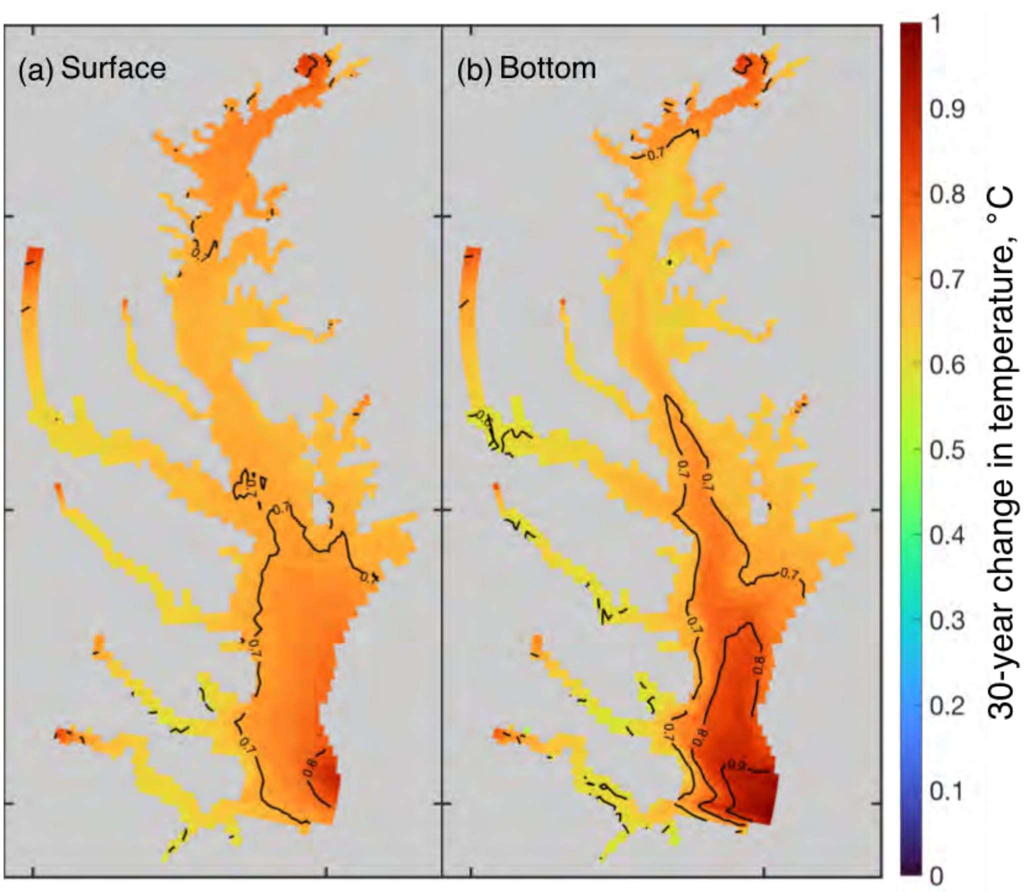


Figure V-9. Left. The 30-year change in observed water column temperatures in depth profiles along the Chesapeake Bay mainstem by month from January through December.

Source: Hinson et al. 2021

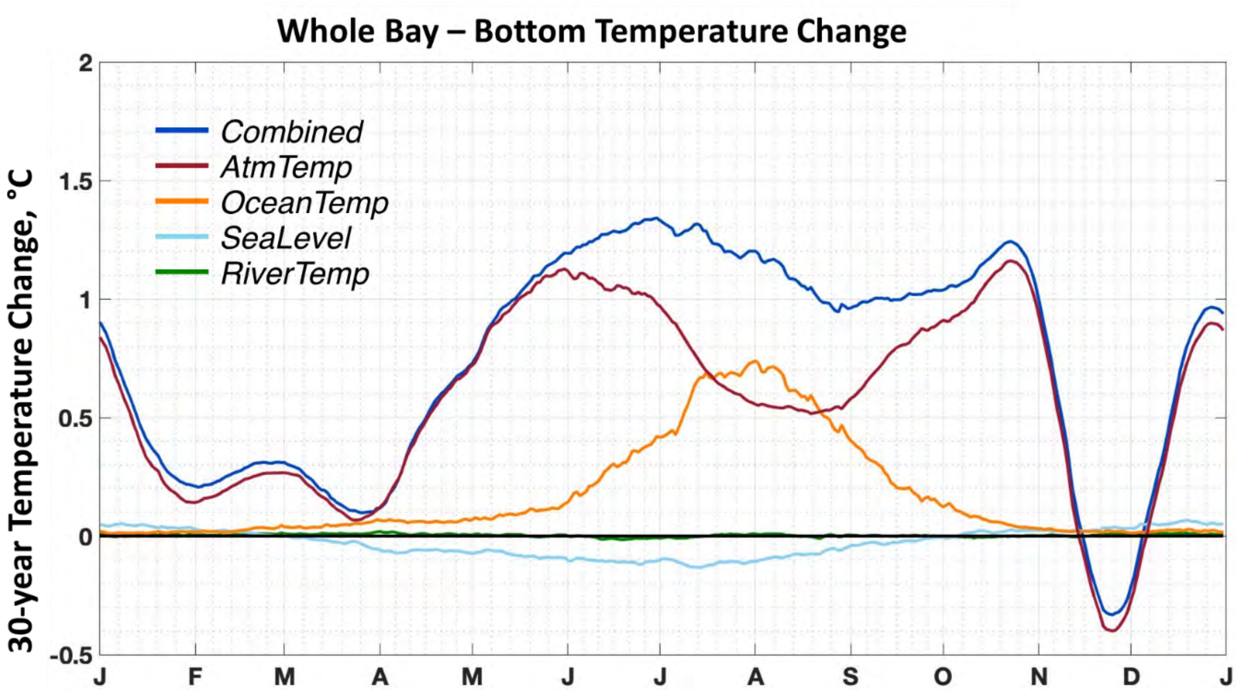
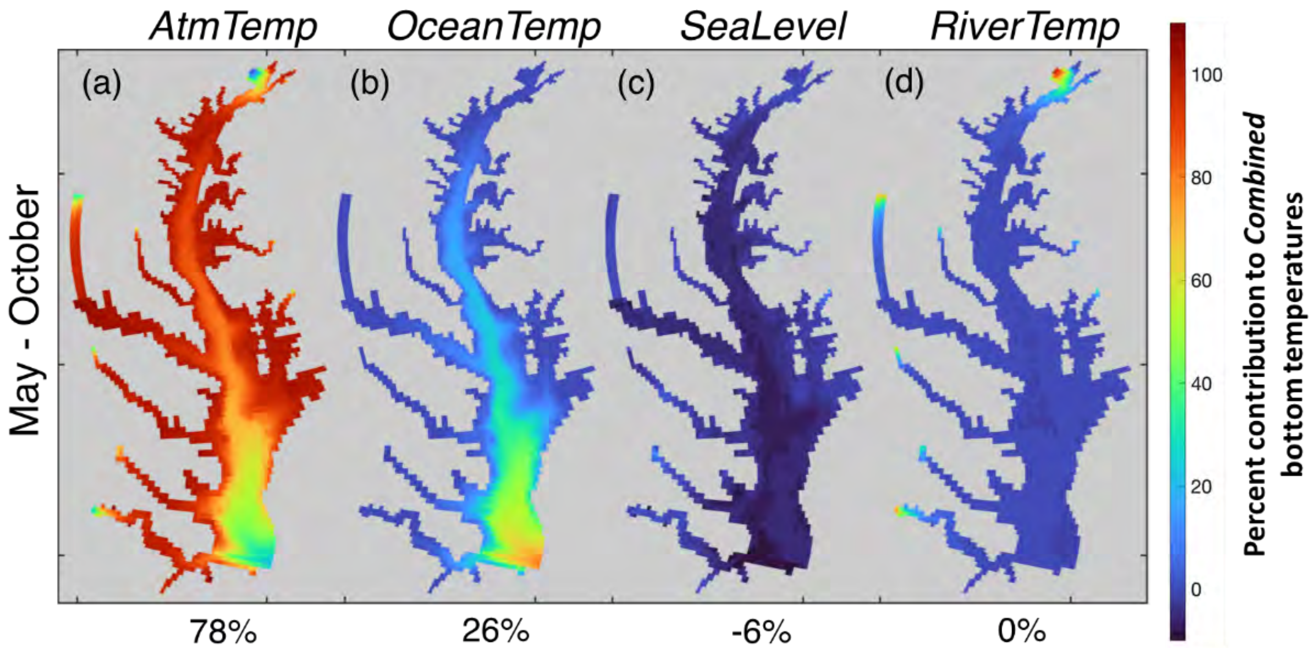


Figure V-10. Model-simulated 30-year bottom water temperature change throughout Chesapeake Bay by month compared with model-simulated bottom water temperature change estimate to be caused by river temperatures, sea level rise, ocean temperature and atmospheric forcings.

Source: Hinson et al. 2021

Atmospheric warming is the dominate influence on increasing Bay water column temperature almost everywhere across the tidal waters, contributing about 78% to the combined effect on changes in bottom Chesapeake Bay water temperatures observed by the past 30 years, equal to about a 0.6°C change over this timeframe (Figure V-11).

The warming the adjacent Atlantic Ocean plays a large role in the changes in southern Chesapeake Bay's water temperatures, with about a 26% contribution to the overall Bay bottom temperatures over the past three decades. Ocean warming alone has contributed at least 50% or greater to the increased Bay water column temperature during the summer months over the past 30 years (Hinson et al. 2021). The increasing temperatures in the rivers flowing into Chesapeake Bay only influence the water column temperatures of the immediate tidal fresh reaches of the tidal tributaries, making no measurable contribution to observed changes in bottom Chesapeake Bay water temperatures observed by the past 30 years. Sea level rise is estimated to slightly cool Bay water column temperatures across the tidal waters, contributing an offsetting 6% cooling contribution to the overall Bay bottom temperatures over the past three decades, about 0.1°C difference over this timeframe (Hinson et al. 2021).



Implications for Ecosystem Processes

Watershed Ecosystem Processes

Water temperature affects all chemical and biological processes of aquatic organisms, as well as being directly linked to survival for temperature-sensitive organisms like brook trout. Water temperature integrates what is happening on the land (e.g. forested, urban impervious), and affects the way nutrients and other pollutants behave in the water column.

Temperatures can vary naturally along the length of a stream, from cold temperatures near a source of meltwater to higher temperatures near its outlet to the tidal water. The temperature at any given point is a product of many different factors, including sources of water (for example, melted snow, a recent rainstorm, or groundwater), the amount of water in the stream (streamflow), air temperature, plants along the bank (for example, trees that provide shade), and the amount of development within the watershed. Over time, however, an area's climate has the strongest natural influence on a stream's temperature. Higher temperatures reduce levels of dissolved oxygen in the water, which can negatively affect the growth and productivity of aquatic life. Persistently warmer temperatures in streams can accelerate natural chemical reactions and release excess nutrients into the water.

Despite the wide variability of the streams and rivers with respect to watershed area, channel geometry, aspect, elevation, thermal capacity, the presence or absence of riparian buffers, microclimate conditions, and land cover, on the whole, water temperature increased from 1960 to 2010. For sites with significantly increased water temperature, 85 % of the variability could be explained by increased atmospheric temperature, despite increased streamflow at some sites (Rice and Jastram 2015).

Estuarine Ecosystem Processes

Tian et al. 2021 reported that increasing Chesapeake Bay water column temperatures will result in reduced oxygen saturation, increased biological rates, and increased stratification of the water column. Their research focused on better understanding how changing oxygen solubility affects dissolved oxygen concentrations in the bottom waters of a stratified Chesapeake Bay.

Higher water temperature reduce the amount of oxygen which can become soluble in water, forming dissolved oxygen. The higher water temperatures will also increase the remineralization rate, that is the natural bacterial decomposition of organic matter into nitrogen, phosphorus and carbon, internally fueling growth of algae. Both of these processes lead to further expansion of and sustaining existing hypoxic (low dissolved oxygen) and anoxic (no dissolved oxygen) conditions in the deeper bottom waters of the Bay mainstem and lower tidal tributaries.

Running a series of scenario simulations using Chesapeake Bay Water Quality Model to determine the magnitude of various mechanisms controlling the effect of increasing water temperature on dissolved oxygen in the Chesapeake Bay, Tian et al. 2021 reported the following findings. They estimated the average hypoxic volume in the summer would increase by 9% from 1995 to 2025 as air temperature increases by 1.06°C and water temperature by 0.9°C. Of the three major drivers of water temperature change impacts, the change in dissolved oxygen solubility contributes 55% to the model projected change in hypoxic volume, biological rates 33%, and stratification 11%.

Off the mouth of the Rappahannock River, the abrupt change in bathymetry and "the convergence between seaward-moving freshwater and landward-moving saltwater causes downwelling and enhanced vertical mixing which introduces surface water of higher temperature to the deep channel and accelerates organic matter remineralization and oxygen consumption in deep waters" (Tian et al. 2021). As surface water dissolved oxygen concentrations will decrease under continued warming of the climate due to lower oxygen solubility, surface waters with even lower dissolved oxygen concentrations will flux to the deep channel further exacerbating development of low to no dissolved oxygen conditions in the deep channel of Chesapeake Bay.

Hinson et al. 2021 reported "on average during the period from May to October, a time of particular interest since it encompasses the bottom hypoxia season, there is more warming in the shallower southernmost extent of the mainstem than in the rest of Chesapeake Bay. Combined with the findings reported by Tian et al. 2021, the warming of the southern Chesapeake Bay mainstem waters will further exacerbate the increased impact of warming water temperatures on low and no dissolved oxygen conditions in the deeper channels of the Chesapeake Bay mainstem to the north.

E. Evaluation

Key Findings

A U.S. Geological Survey analysis of non-tidal stream temperatures from 1960 through 2010 documented that average non-tidal stream temperatures increased 2.52 °F from 1960 to 2010, while air temperatures increased 1.99 °F (Rice and Jastram 2015). These major findings were:

- Analysis of both air and stream-water temperatures for two periods, 1961–1985 and 1985–2010, relative to the climate normal period of 1971–2000, indicate that the 1985-2010 period was statistically significantly warmer than the 1961-1985 period for both mean air temperature and stream-water temperature;
- Across the Chesapeake Bay watershed and the surrounding region, statistically significant temporal trends of 0.023 °C per year for air temperature and 0.028 °C per year for stream-water temperature were determined;
- From 1960 through 2010, water temperature increased significantly at 53 of 129 stations analyzed in the region;
- Stream-water temperature decreased significantly at 7 of those 129 stations over the same period;
- In areas where major dams were and the land cover was principally deciduous forest, stream-water temperatures were increasing slower than air temperatures, whereas agriculture-dominated regions in the absence of major dams were correlated with stream-water increasing faster than air temperatures;
- Increasing stream-water temperature trends are detected despite increasing trends in streamflow in the northern Chesapeake Bay watershed and surrounding region; and
- Increases in water temperature occurred at the greatest rates in the southern Chesapeake Bay watershed and surrounding region.

Rice and Jastram (2015) concluded "continued warming of contributing streams to Chesapeake Bay likely will result in shifts in distributions of aquatic biota and contribute to worsened eutrophic conditions in the bay and its estuaries."

There is significant evidence of widespread increases in Chesapeake Bay water column temperatures reported independently by an array of different research and data analysis teams over the past decade. And recently, a research team composed of scientists from the Virginia Institute of Marine Science and Penn State University published an in-depth evaluation of the major drivers for the observed increases in Chesapeake Bay water column temperatures (Hinson et al. 2021). Their major findings are summarized as:

- Atmospheric forcings and warming ocean boundary are the most pertinent driving forces to future warming of Chesapeake Bay water temperatures;
- Atmospheric forcings (air temperature increases/decreases) main driver influencing Bay water temps year-round, but effects lessened during summer;
- Warming ocean boundary effects are important in summer (influenced =/> 50% warming), but small otherwise during the rest of seasons;
- Sea level rise slightly cools Chesapeake Bay mainstem waters from April-September and warms bottom waters in winter;

- River temperatures produce little to no warming in the Chesapeake Bay's mainstem, but still influence temperature in the tidal fresh and low salinity waters in the upper reaches of the tidal tributaries and embayments; and
- Future warming of Chesapeake Bay waters will depend not only on global temperature trends, but also on regional circulation patterns in mid-Atlantic waters which are currently warming faster than the atmosphere.

Tian et al. 2021 warned that increasing Chesapeake Bay water temperatures will result in increased volumes of low dissolved oxygen due to direct effects on oxygen solubility, biological processes rates and water column stratification.

Management Implications

For freshwaters, there are implications for potential shifts in floral and faunal species distributions. Streams at the upper end of the water temperature distribution may become unsuitable habitat for certain cool-water fish species (Eaton and Scheller 1996; Isaak et al. 2012). Increasing water temperature also may make some streams suitable for species not currently present, allowing warm-water species, including invasive species and pathogens, to move into previously cool-water habitats. Streams draining forested watersheds with major dams warmed more slowly than other watersheds and are likely to become even more important as refugia for cool-water species in a warming world (Rice and Jastram 2015). In addition, warmer water temperatures in the watershed's streams and rivers could decrease the availability of water used for power plant cooling and could have other interactions with built infrastructure[2].

Reducing the water temperatures of the river flowing into Chesapeake Bay will have no to a very minimal to affect the continued warming of most of Chesapeake Bay's water column temperatures. River water temperatures do influence the water temperatures of the tidal tributary reaches just down tide of the river inputs as well as the Susquehanna Flats and the upper Bay mainstem reach down to about Back River on the western shore. These tidal fresh reaches provide for important spawning, nursery and year-round habitats for anadromous (e.g., striped bass), semi-anadromous (e.g., white perch) and resident (e.g., largemouth bass) fish populations which are directly affected by changes in tidal water temperature.

Changing the magnitude of the two major influences on Bay water temperatures—atmospheric forcings and ocean warming—are clearly management and human behavioral challenges to be addressed at the global to local scales, collectively. However, the resultant effect of warmer water temperatures on biological, chemical and other ecosystem process will very likely require additional nutrient and sediment load reductions to mitigate these impacts on the Bay's living resources. Continue warming of the Bay waters will affect the temperature thresholds critical to the survival, growth, behavior and migration patterns of individual species and entire communities as well as their prey and the suitability of their surrounding habitats. Further research on the warming of Chesapeake

[2] Pennsylvania Climate Impacts Assessment.

Bay waters must not only better understand the impacts on water temperature from atmospheric changes, but also changes in the adjacent coastal ocean.

F. Bibliography

References Cited

Cochrane, D. and G.H. Orcutt. 1949. Application of Least Squares Regression to Relationships Containing Auto-Correlated Error Terms. Journal of the American Statistical Association, 44, 32-61.

Ding, H. and A.J. Elmore. 2015. "Spatio-Temporal Patterns in Water Surface Temperature from Landsat Time Series Data in the Chesapeake Bay, U.S.A." *Remote Sensing of Environment* 168: 335–348. https://doi.org/10.1016/j.rse.2015.07.009.

Eaton and Scheller. 1996. "Effects of climate warming on fish thermal habitat in streams of the United States" *Limnology and Oceanography* 41 (5), 1109-1115. https://doi.org/10.4319/lo.1996.41.5.1109

Falcone. 2011. "GAGES-II: Geospatial Attributes of Gages for Evaluating Streamflow" https://water.usgs.gov/lookup/getspatial?gagesII_Sept2011

Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A., and Gilroy, E.J. 2020. Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chapter A3, 458 p., https://doi.org/10.3133/tm4a3. [Supersedes USGS Techniques of Water-Resources Investigations, book 4, chapter A3, version 1.1.]

Hinson, K., M.A.M. Friedrichs, P. St-Laurent, F. Da, R.G. Najjar. 2021. "Extent and Causes of Chesapeake Bay Warming." *Journal of the American Water Resources Association* 1–21. http://doi.org/10.1111/1752-1688.12916

Isaak, D.J., Wollrab, S., Horan, D. *et al.* Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. *Climatic Change* 113, 499–524 (2012). https://doi.org/10.1007/s10584-011-0326-z

Jastram, J.D., and K.C. Rice. 2015. Air- and stream-water-temperature trends in the Chesapeake Bay region, 1960–2014: U.S. Geological Survey Open-File Report 2015–1207, 28 http://dx.doi.org/10.3133/ofr20151207.

Linker, L. C., 2020. "Influence of Climate Change Risk on the Chesapeake Bay Open-Water Dissolved Oxygen Water Quality Standard." For distribution to the Chesapeake Bay Program Modeling Workgroup and Water Quality Goal Implementation Team. July 29, 2020. Chesapeake Bay Program Office, Annapolis, MD.

Murphy, R.R., E. Perry, J. Harcum, and J. Keisman. 2019. A Generalized Additive Model Approach to Evaluating Water Quality: Chesapeake Bay Case Study. *Environ. Modelling Software* 118: 1-13. https://doi.org/10.1016/j.envsoft.2019.03.027.

Preston, B.L. 2004. Observed Winter Warming of the Chesapeake Bay Estuary (1949-2002): Implications for Ecosystem Management. *Environmental Management* 34: 125–139. https://doi.org/10.1007/s00267-004-0159-x.

Rice, K.C., and J.D. Jastram. 2015. Rising air and stream-water temperatures in Chesapeake Bay region, USA: *Climatic Change*, v. 128, p. 127-138. https://doi.org/10.1007/s10584-014-1295-9

Stewart, R. 2018. *Integrated Report on Water Quality Trends in Virginia*. Virginia Department of Environmental Quality, Richmond, Virginia.

Tian, R., C.F. Cerco, G. Bhatt, L.C. Linker, and G.W. Shenk. 2021. Mechanisms Controlling Climate Warming Impact on the Occurrence of Hypoxia in Chesapeake Bay. *Journal of the American Water Resources Association* 1–21. https://doi.org/10.1111/1752-1688.12907.

Additional Resources

Kyle Hinson's presentation on the "Extent and Causes of Chesapeake Bay Warming" as presented to the Chesapeake Bay Program Partnership's Modeling Workgroup can be accessed at: https://www.chesapeakebay.net/channel_files/42529/hinson_bay_warming_-_20210407.pdf

The "baytrendsmap" link that can be used to generate custom maps and explore the GAM trend analysis results is accessible at: https://baytrends.chesapeakebay.net/baytrendsmap/

EPA Climate change indicator can be accessed at: https://www.epa.gov/climate-indicators/climate-change-indicators-stream-temperature

Pennsylvania Climate Impacts Report can be accessed at: https://files.dep.state.pa.us/Energy/Office%20of%20Energy%20and%20Technology/OETDPortalFiles/Climate%20Change%20Advisory%20Committee/2020/12-22-20/2021_IA_Draft_Final_12-15-20.pdf

Stream temperature EPA technical documentation can be accessed at: https://www.epa.gov/sites/production/files/2016-08/documents/stream-temperature_documentation.pdf

Appendix J

Synthesis Element 6: Understanding the Factors and Geographies Most Influencing Water Temperatures in Local Waters Throughout the Watershed and Across all the Bay's Tidal Waters

Synthesis Element 6: Understanding the Factors and Geographies Most Influencing Water Temperatures in Local Waters Throughout the Watershed and Across all the Bay's Tidal Waters

At a Glance Summary

- Development of a Phase 7 Chesapeake Bay Watershed Model at a much finer geographic scale is necessary to make predictions in changes in the watershed's water temperature for streams and rivers directly relevant to watershed living resource managers.
- Assessment of climate change's impact on the ability to achieve the states' Chesapeake Bay open-water dissolved oxygen water quality standards in shallow waters will require a new Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model.
- There is a need to understand just how feasible and what are the costs for developing Phase 7 versions of both the existing Bay watershed and Bay water quality models at these respective smaller scales are going to be.

A. Contributors

Rich Batiuk, CoastWise Partners; Gopal Bhatt, Pennsylvania State University/Chesapeake Bay Program Office; Lewis Linker, U.S. Environmental Protection Agency Chesapeake Bay Program Office; Gary Shenk, United State Geological Survey/Chesapeake Bay Program Office; Richard Tian, University of Maryland Center for Environmental Sciences/Chesapeake Bay Program Office; and Guido Yactayo, Maryland Department of the Environment.

B. Resources

Published papers cited as references; Maryland Department of the Environment Stream Temperature Model calibration results generated by Guido Yactayo; and Chesapeake Bay Water Quality Model scenario results generated by Richard Tian.

C. Approach

Engaged expert modelers to provide the latest insights into the stream/river and tidal water temperature simulation capabilities of the suite of models being used by the Chesapeake Bay Program partnership and its partners in ongoing climate change, stream and tidal water temperature change evaluations.

D. Synthesis

Existing Watershed Stream and River Water Temperature Simulation Capabilities

CBP Phase 6 Chesapeake Bay Watershed Model

The Chesapeake Bay Program's (CBP) Phase 6 Chesapeake Bay Watershed Model (Chesapeake Bay Program 2020) has two linked components. The Chesapeake Assessment Scenario Tool or CAST is the time-averaged watershed model used interactively by the CBP partnership and others to estimate long-term changes in nitrogen, phosphorus, and sediment loads based on changes in management. However, CAST has no temperature simulation capability.

On the other hand, the dynamic model component of the Phase 6 Chesapeake Bay Watershed Model (Phase 6 dynamic model) runs on an hourly time step and simulates river reach temperature. The long-term outputs for nitrogen, phosphorus, and sediment, often with temperature corrected reaction rates, in the Phase 6 dynamic model are constrained to equal the predictions from CAST. The Phase 6 dynamic model simulates temperature to inform the biological reaction rates of the dynamic nutrient simulation within the rivers. Flow and temperature in the Phase 6 dynamic model are simulated using Hydrologic Simulation Program – FORTRAN.

Hourly air temperature from a reanalysis product is used as in input to the Phase 6 dynamic model river reach simulation and also to calculate potential evapotranspiration (Chesapeake Bay Program 2020 section 10.2). Annual average temperature is used to calculate parameters controlling soil and groundwater temperature. The groundwater temperature is a set spatially varying constant for each month of the year, but monthly constants were not adjusted in the climate change scenarios as the hourly air temperature was. Upper layer soil and stormflow temperatures are parameterized such that they are essentially a damped version of the air temperature time series (Chesapeake Bay Program 2020 section 10.6.2.1). Temperature simulation in rivers is a heat balance from the constituents of advection, atmospheric interaction, radiation and bed heat transfer.

Seasonal simulation of temperature in the Chesapeake Bay watershed's rivers is generally good, however, there are several areas for potential improvement in the temperature simulation.

- Surface flow and stormwater temperature will respond to climate change in the current dynamic model, however, the parameterization of dynamic model surface flow from the land should ideally respond to climate change as well.

- Groundwater temperatures should be made to respond to climate change in the Phase 7 dynamic model.

- The current scale of the Phase 6 dynamic model river simulation is for larger streams and rivers with greater than 100 cubic feet per second average flow rates. But the most temperature-sensitive species in freshwater areas are generally found in streams smaller than the Phase 6 dynamic model river-reach scale for segments which average 70 square miles in area. A Phase 7 scale of river reaches for model segments of about one square mile are more appropriate for assessment of river and stream living resources.

MDE Gwynns Falls Model

The Maryland Department of the Environment has calibrated and applied a version of the deterministic and dynamic watershed model called Soil Water Assessment Tool or SWAT to the Gwynns Falls watershed. The SWAT model was used because it also contains a physically based and spatially semi-distributed stream temperature module (Maryland Department of the Environment 2020). The Gwynns Falls watershed model delineation was performed utilizing Baltimore County's 1:2400 scale hydrography network information and a 30-meter digital elevation model (DEM). This resulted in about 100 river segments within the study area. Figures VI-1 and VI-2, respectively, show the study area and the model segmentation.

Model accuracy is reported for all calibration stations, and for both hydrology and stream temperature in Table A4 and A6, respectively, in Maryland Department of the Environment 2020. There are also graphs that show observed and simulated results. Overall calibration statistics indicate the model was able to produce a good hydrology and stream temperature calibration (Figure VI-3).

Current Model Simulation Findings

Chesapeake Bay water temperature increases due to climate change during the period 1995-2025 are estimated to be approximately 1^{o} C, mirroring the observed and projected changes in air temperature. An extensive analysis of the effect of climate change on dissolved oxygen in the Bay has been performed by the CBP (Shenk et al., 2021), however, detailed estimates of the modeled effects on the Chesapeake Bay watershed's river temperatures were not part of the analysis.

Existing Tidal Tributaries, Embayments and Mainstem Water Temperature Simulation Capabilities

The CBP's tidal Water Quality and Sediment Transport Model computes temperature through a conservation of heat equation. Only advection and exchange with the atmosphere are considered. Temperature is generally well-simulated and is calculated in both the hydrodynamic model and the water quality model to verify the calculations of each.

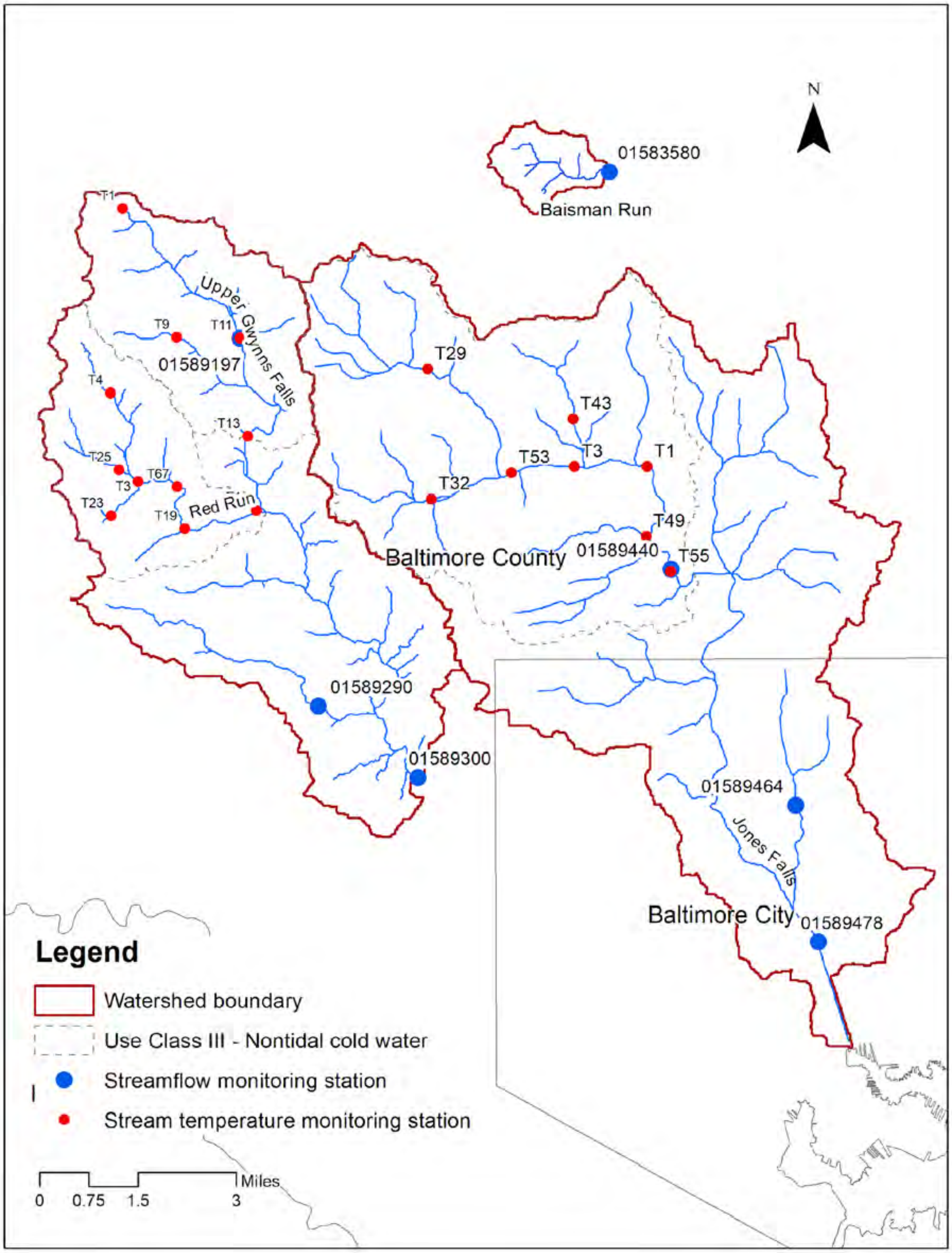


Figure VI-1: Gwynns Falls, Jones Falls, and Baisman Run streamflow and stream temperature monitoring stations.

Source: Maryland Department of the Environment 2020

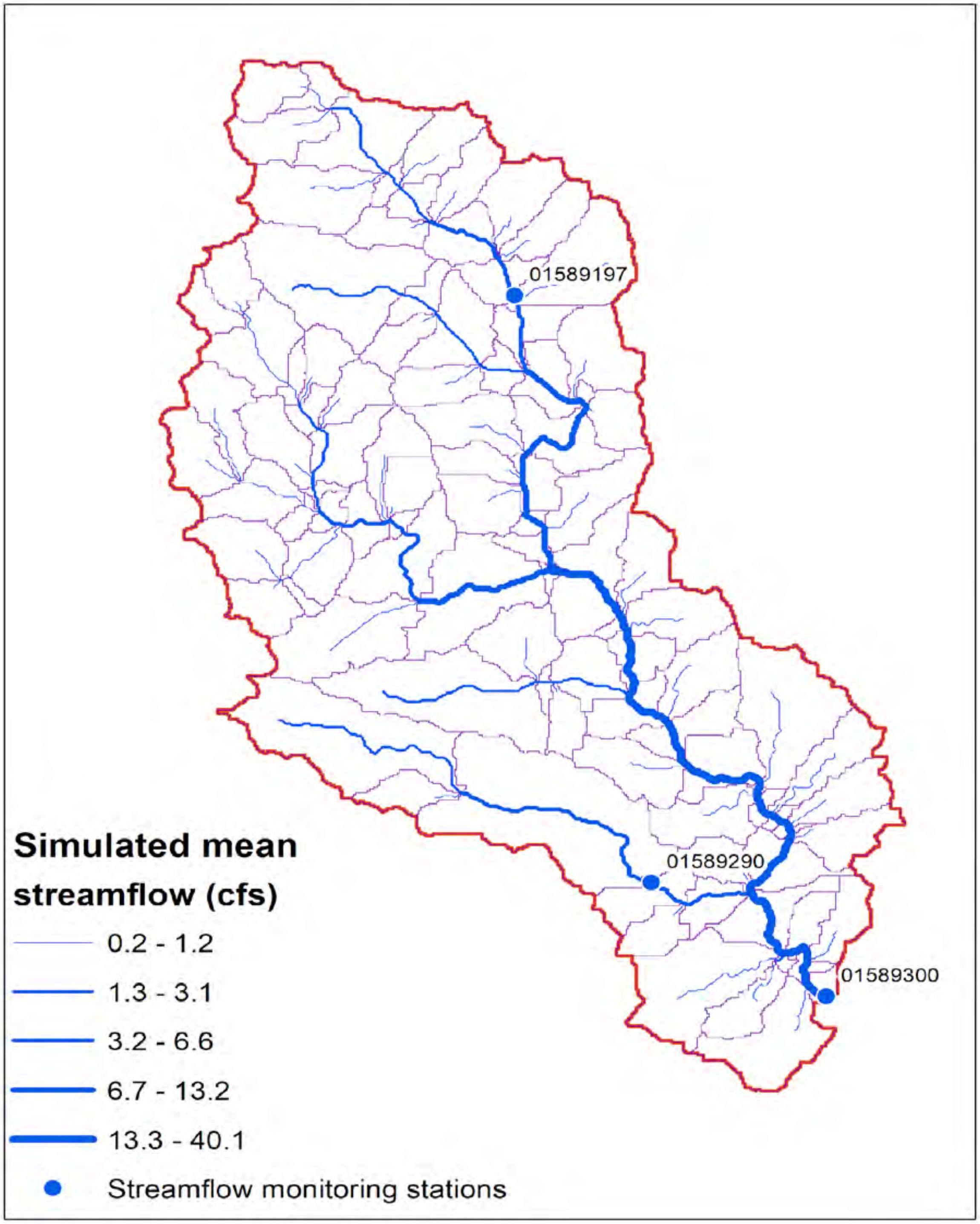


Figure VI-2: Map showing the distribution of summer streamflow for all river segments, as represented in the SWAT model.

Source: Maryland Department of the Environment 2020

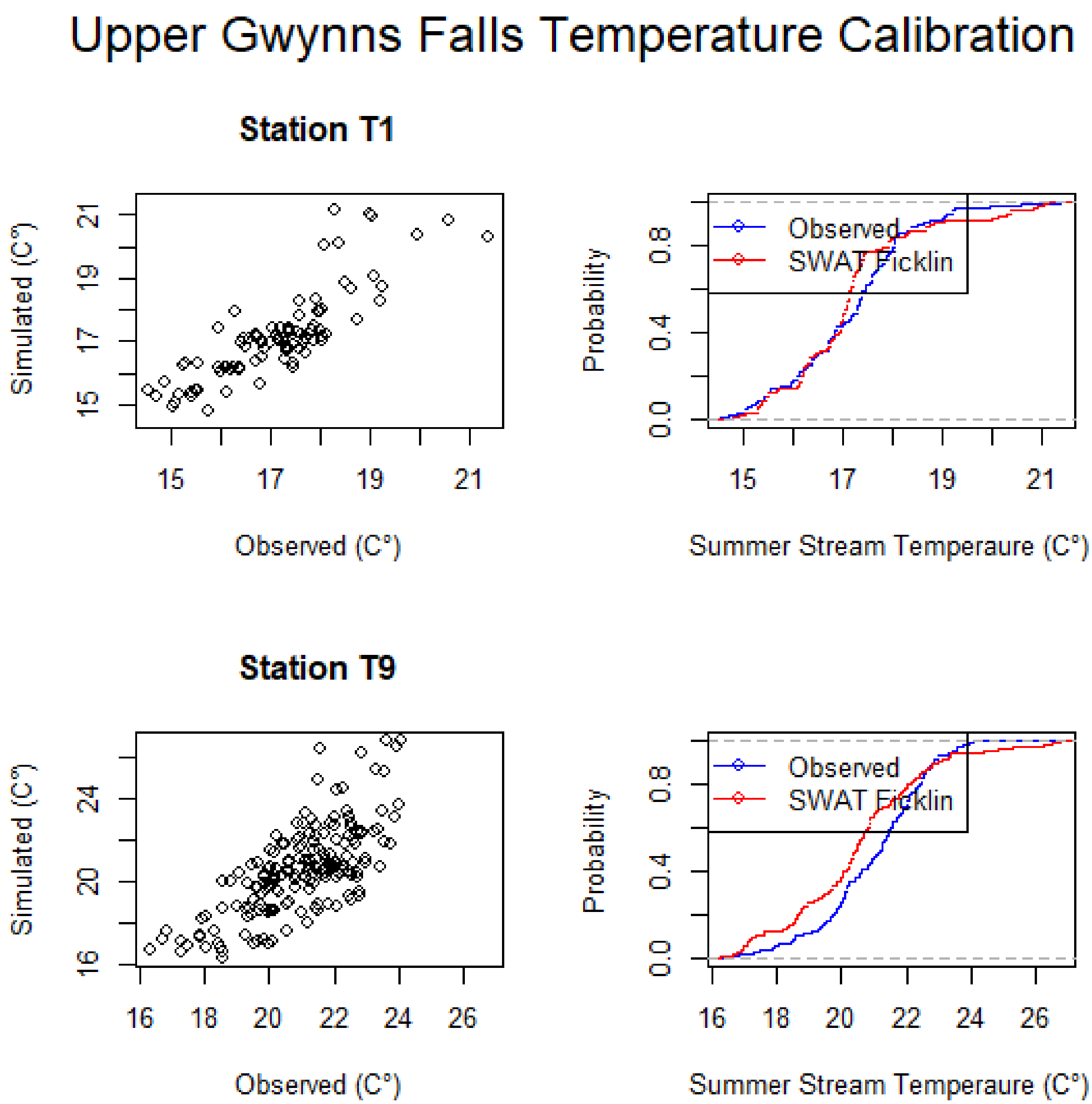


Figure VI-3: Observed and Simulated Daily In-Stream Summer Temperature in Upper Gwynns Falls Cold Water Streams.

Source: Maryland Department of the Environment 2020

Current Model Simulation Findings

Temperature increases decrease tidal dissolved oxygen through three primary mechanisms: lower oxygen solubility, increased stratification and increased biological rates. A recent analysis by Tian et al., 2021, found that solubility was the primary effect with 55% of the total, followed by biological rates (33%), and stratification 11%) (Figure VI-4).

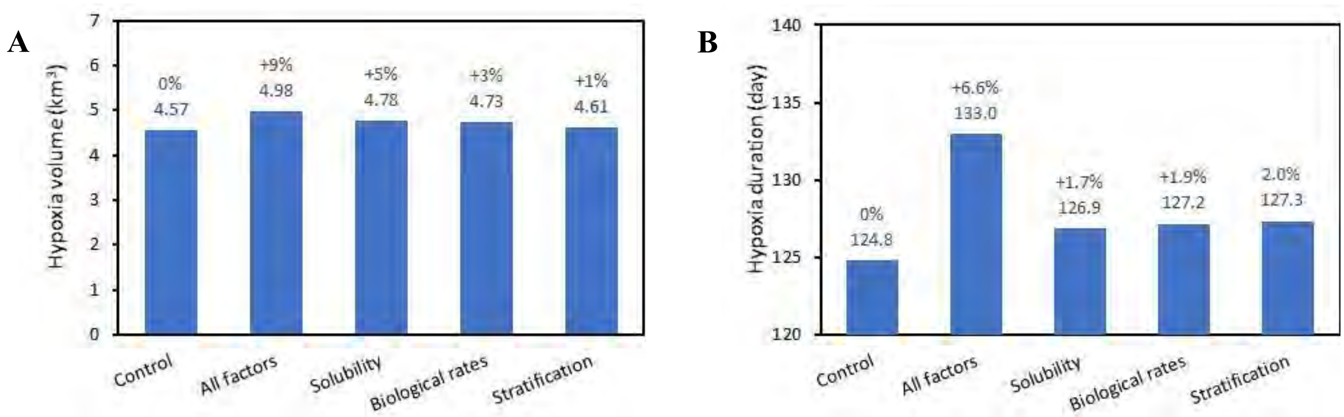


Figure VI-4. (A) Hypoxic volume (km3) in the whole Bay averaged in summer from June through September over 10 years (B) Hypoxic duration(days) at the monitoring station CB4.3C for the entire year, averaged over 10 years of simulation. Control: The control run; All factors: All warming effects; Solubility: The same as the control run but DO solubility computed under CWC; Biological rates: The same as the control run but the biological rates were calculated under CWC; Stratification: The same as the control run but with turbulence diffusivity under CWC. Percentages are the relative changes compared to the control run.

Source: Tian et al. 2021

How the Phase 7 Models Will Improve Our understanding of Water Temperature in the Chesapeake Bay Watershed and Tidal Waters

Chesapeake Bay Watershed Model

The CBP partnership is expected to give formal direction to the CBP Modeling Workgroup on the prioritization of improvements in the Phase 7 Chesapeake Bay Watershed Model during an October 2021 meeting. Therefore, the expectations provided below are provisional.

The Phase 7 Chesapeake Bay Watershed Model is currently being developed on a National Hydrologic Database 100,000 scale, which has an average watershed size of approximately one square mile, compared to the 70 square mile average in the Phase 6 Chesapeake Bay Watershed Model (Figure VI-5). This change in scale will allow the CBP to make predictions at a scale more relevant to living resource managers in the watershed. River reach-scale processes controlling temperature are important for living resources, however, they will be difficult to validate everywhere given the lack of temperature observations at the fine scale.

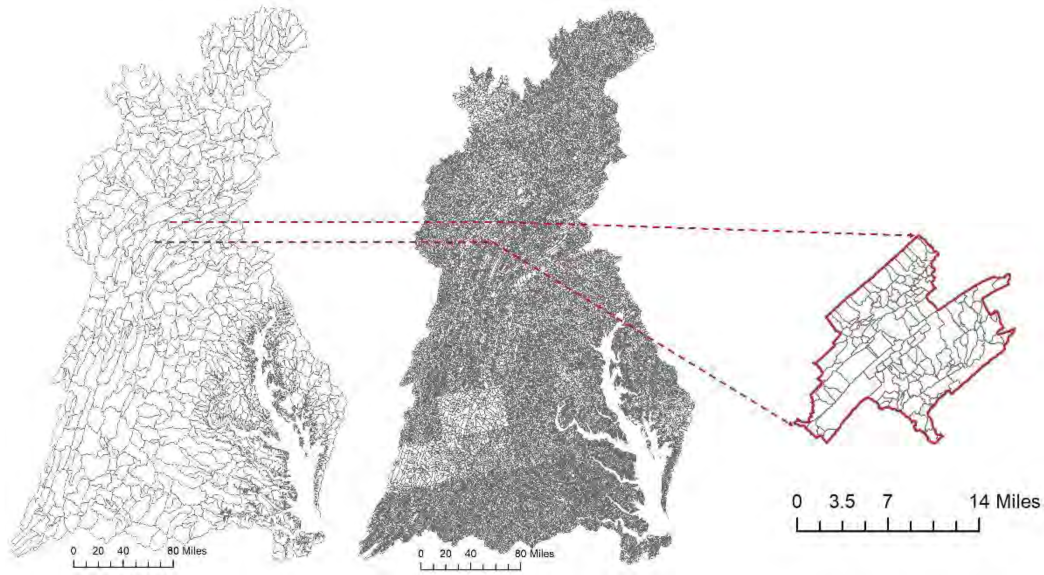


Figure VI-5. River simulation scale in Phase 6 and proposed Phase 7 Chesapeake Bay Watershed Models.

Chesapeake Bay Water Quality and Sediment Transport Model

In the tidal waters of Chesapeake Bay, Delaware, District of Columbia, Maryland and Virginia's open-water dissolved oxygen state water quality standards are based on protection of living resource habitat. The 2010 Chesapeake Bay TMDL was based on attainment of the summer open water monthly mean criteria of 5 mg/l (5.5 mg/l in tidal fresh waters), which was established to protect the growth of larval, juvenile, and adult fish and shellfish (U.S. Environmental Protection Agency 2010).

Under climate change conditions, the average annual tidal water temperatures are estimated to increase by 1° C over the three-decade period between the hydrology used for the Chesapeake TMDL (1991-2000) and the year 2025 (Shenk et al., 2021). By 2055 the average tidal water temperature is estimated to increase by 2° C for the 60 years between 2055 and 1995. Climate change temperature increases in Chesapeake tidal waters are inevitable over the next
half-century, are global in origin, and are largely beyond CBP management and control.

Consequently, challenges in maintaining achievement of an open-water dissolved oxygen water quality criteria of 5 mg/l in all open-water designated uses at all times will inevitably increase throughout the next half-century. This is particularly true in the shallow water portions of the open-water dissolved oxygen designated uses of Chesapeake Bay, which are generally defined as those areas less than 2 meters in depth (U.S. Environmental Protection Agency 2010).

However, the minimum depth represented in the 2017 Chesapeake Bay Water Quality and Sediment Transport Model, used for the current assessment of climate change risk to tidal water quality standards, is 2 meters. Consequently, the depth of the nearshore areas is inaccurately represented. Until now, the Chesapeake Bay Water Quality and Sediment Transport Model was sufficient for open-water dissolved oxygen assessment, but in a changing climate with increasing shallow water temperatures the current model's simulation is unsuitable for shallow water open-water dissolved oxygen water quality standards attainment assessment.

Nevertheless, assessment of open-water dissolved oxygen climate risk is needed in shallow waters. Going forward, a new Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model is required which can:

1) Simulate shallow water at a finer scale;

2) Allow for an unstructured model grid to fit complicated shorelines;

3) Simulate wetting and drying of the intertidal region;

4) Project tidal wetland and SAV migration with sea level rise;

5) Estimate SAV responses to climate change;

6) Assess living resource co-benefits; and

7) Provide a state-of-the-art assessment of the important interface between land and water in the Chesapeake Bay estuary.

The estuarine model approach for simulation of shallow water habitats described in the CBP Scientific and Technical Advisory Committee's report on the *Chesapeake Bay Program Modeling in 2025 and Beyond: A Proactive Visioning Workshop* outlines the direction needed for a sufficient simulation of open-water dissolved oxygen in shallow Chesapeake Bay waters under climate change conditions (Hood et al. 2019).

E. Evaluation

Key Findings

- The Phase 6 Chesapeake Bay Watershed Model is sufficient for predicting climate change effects on river temperatures reaching the tidal waters, however, the simulation of climate change would be improved by adjusting ground water temperatures to future climate conditions.

- Development of the Phase 7 Chesapeake Bay Watershed Model at a much finer geographic scale would increase the ability to make predictions in changes in the watershed's water temperature for streams and rivers directly relevant to watershed living resource managers such as cool- and coldwater fisheries in headwater streams.

- Maryland Department of the Environment's development of the SWAT model for simulating stream temperatures will help understand the feasibility and accuracy of temperature simulations at a very local scale prior to development of the next phase of the Chesapeake Bay Watershed Model.

- Climate change-driven Chesapeake Bay tidal water temperature increases will continue to have a significant influence on the ability to attain the states' Chesapeake Bay dissolved oxygen water quality standards.

- Assessment of climate change's impact on the ability to achieve the states' Chesapeake Bay open-water dissolved oxygen water quality standards in shallow waters will require a new estuarine model system.

Management Implications

Chesapeake Bay Watershed's Streams and Rivers

In the watershed, the proposed finer scale of the Phase 7 Chesapeake Bay Watershed Model is expected to provide an quantifiable improvement in simulated hydrology and sediment fate and transport. The improvement in simulated flow and sediment loads will further improve the nutrient simulation beyond the Phase 6 Chesapeake Bay Watershed Model simulation. Also, the number of calibration stations for river and stream flow will almost double, which will further increase confidence in the Phase 7 model assessment. Finally, the finer scale of Phase 7 Chesapeake Bay Watershed Model throughout the watershed will allow an improved assessment of impacts on coldwater and warmwater fisheries.

Given a Phase 7 Chesapeake Bay Watershed Model scale of river reaches of about one square mile is essential to accurately simulating stream water temperatures, there is a need to understand just how feasible and cost-effective developing a model at this scale is going to be. The amount of time involved and cost of building the capability to model at this fine scale of resolution are questions which need to be answered and put in content for the timing of the management decisions depending on this next version of the watershed model.

Chesapeake Bay Tidal Waters

A Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model should be used to assess the risk to attainment of the states' Chesapeake water quality standards under 2035 climate change conditions. The finer scale of an unstructured grid model would allow the assessment of the shallow open-water dissolved oxygen concentrations under climate change conditions for the first time.

The 2010 Chesapeake Total Maximum Daily Load (TMDL) requires all of the states' Chesapeake Bay dissolved oxygen, SAV/water clarity, and chlorophyll *a* water quality standards to be fully assessed and attained. With the fine-scale unstructured grid of the Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model, the ability to do this assessment under climate change conditions of increased temperatures and sea level rise will be substantially improved.

The proposed Phase 7 Chesapeake Bay Water Quality and Sediment Transport Model would: 1) simulate shallow water at a finer scale and depth increments; 2) use an unstructured model grid to fit complicated shorelines; 3) simulate wetting and drying of wetlands and the intertidal region; 4) project tidal wetland and SAV migration with sea level rise; 5) estimate SAV response to climate change; 6) assess living resource co-benefits; and 7) provide a state-of-the-art assessment of the important interface between land and water in the Chesapeake estuary.

F. Bibliography

References Cited

Chesapeake Bay Program. 2020. Chesapeake Assessment and Scenario Tool (CAST) Version 2019. Chesapeake Bay Program Office. https://cast.chesapeakebay.net/Documentation/ModelDocumentation

Hood, R.R., G. Shenk, R. Dixon, W. Ball, J. Bash, C. Cerco, P. Claggett, L. Harris, T.F. Ihde, L. Linker, C. Sherwood, and L. Wainger. 2019. Chesapeake Bay Program Modeling in 2025 and Beyond: A Proactive Visioning Workshop. Chesapeake Bay Program Scientific and Technical Advisory Committee, Edgewater, MD.

Maryland Department of the Environment. 2020. Gwynns Falls Temperature TMDL Appendix A-Stream Temperature Modeling for TMDL Development and Implementation in Nontidal Coldwater Streams in Maryland. Baltimore, MD.

Shenk, G. W., Bhatt, G., Tian, R., Cerco, C.F., Bertani, I., Linker, L.C., 2021. Modeling Climate Change Effects on Chesapeake Water Quality Standards and Development of 2025 Planning Targets to Address Climate Change. CBPO Publication Number 328-21, Annapolis, MD. 145 pp. file:///C:/Users/gshenk/Downloads/P6ModelDocumentation_ClimateChangeDocumentation%20(4).pdf

Tian, R., C.F. Cerco, G. Bhatt, L.C. Linker, and G.W. Shenk. 2021. "Mechanisms Controlling Climate Warming Impact on the Occurrence of Hypoxia in Chesapeake Bay." Journal of the American Water Resources Association 1–21. https://doi.org/10.1111/1752-1688.12907.

U.S. Environmental Protection Agency. 2010. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. U.S. Environmental Protection Agency Chesapeake Bay Program Office, Annapolis MD. https://www.epa.gov/chesapeake-bay-tmdl/chesapeake-bay-tmdl-document

Appendix K
Synthesis Element 7/8 (Revised): Impacts of BMPs and Habitat Restoration on Water Temperatures: Opportunities to mitigate rising water temperatures

Synthesis Element 7/8 (Revised): Impacts of BMPs and Habitat Restoration on
Water Temperatures: Opportunities to mitigate rising water temperatures

At a Glance Summary

- BMPs can impact stream water temperature through multiple pathways, including modifying air temperature, surface runoff temperature and surface/groundwater interactions.
- Many Urban BMPs are "heaters", while tree planting and buffers show cooling promise over time.
- There are many BMPs that are unlikely to influence water temperature and others that have uncertain water temperature impacts, including agricultural BMPs, stream restoration and wetlands BMPs.
- Over time, the use of "heating" BMPs has grown relative to "cooling" BMPs in the Chesapeake Bay Watershed.
- Additional emphasis is needed to promote the use of cooling BMPs over heating BMPs, especially in watersheds that may be particularly vulnerable to climate change or where there is valuable cold-water habitat.

A. Contributors

Katie Brownson, USFS; Tom Schueler, CSN; Iris Allen, MD DNR Forestry; Frank Borsuk, EPA; Sally Claggett, USFS; Mark Dubin, UMD; Matt Ehrhart, Stroud; Stephen Faulkner, USGS; Anne Hairston-Strang, MD DNR Forestry; Jeremy Hanson, VT; Judy Okay, J&J Consulting; Katie Ombalski, Woods & Waters Consulting; Lucinda Power, EPA CBPO.

B. Resources

The synthesis was primarily developed from a limited review of the scientific literature, as well as several group discussions to formulate the overall approach and provide supporting science.

C. Approach

The group decided to focus efforts on non-tidal and near-shore tidal water temperature, given the limited influence BMPs have on main-stem tidal water temperature. Research by Hinson et al (2021) indicates that atmospheric changes and ocean warming are the driving forces for warming in the Chesapeake Bay, while river inputs have little impact, except at the head of tidal tributaries.

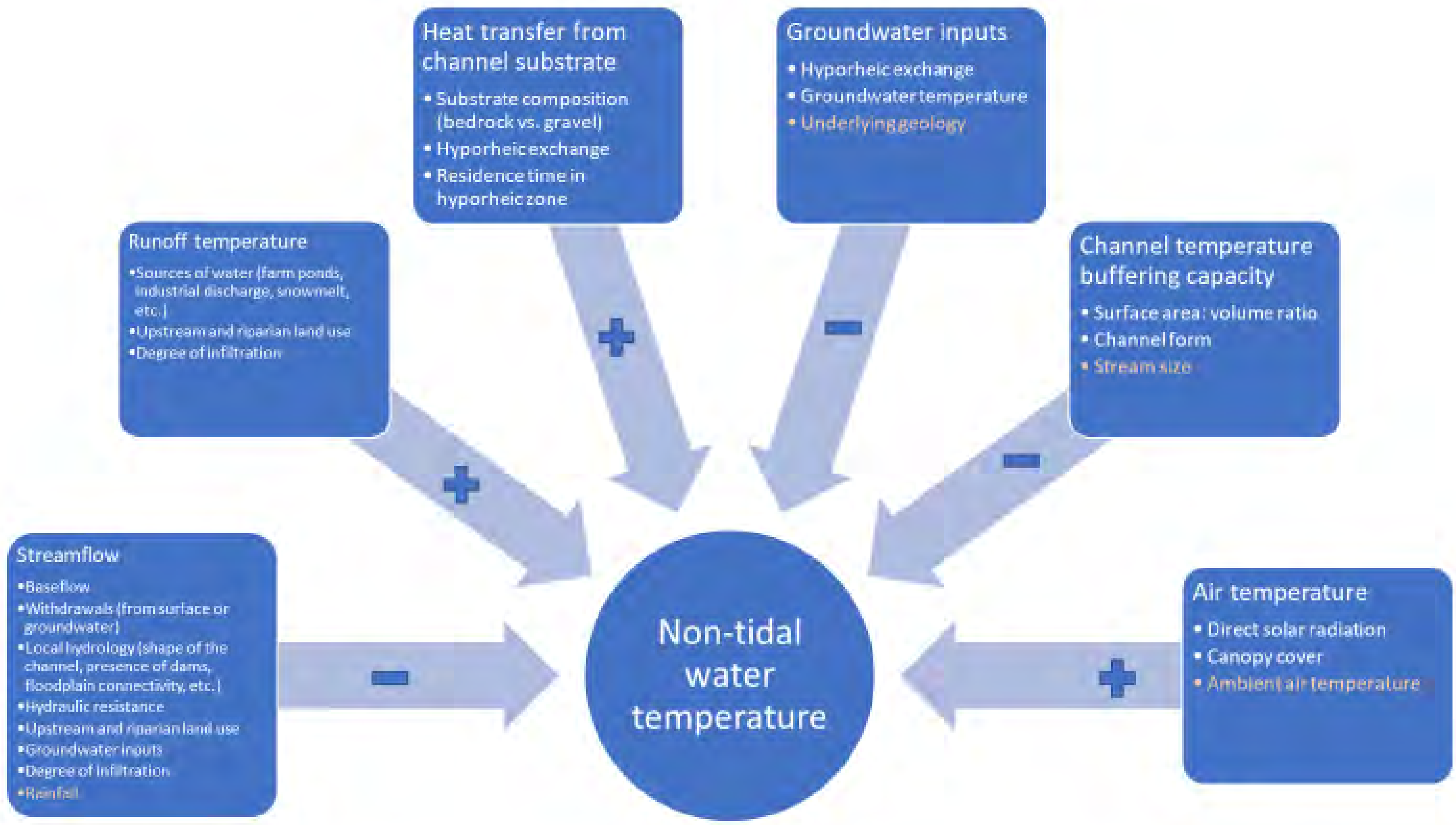
For stream temperature, the group discussed a simple model for assessing the impact of historic and future BMPs on rising stream temperatures using a basic watershed BMP delta-T equation, as follows:

$$[\text{Stream Temp } \Delta] =$$

$$\sum [\Delta \text{ Land Use}] + [\text{Upland BMP } \Delta] + [\text{Stream Corridor } \Delta] + [\text{Corridor BMP } \Delta] + [\text{Riverine } \Delta]$$

- *Land Use* Temp Effect: ambient stream temps as influenced by heat island effect: Forest << Pasture/Crops << Suburban <<< Urban. The cumulative land use effect is generally + relative to the baseline.
- *Upland BMP* Effect: reflects how ponding, infiltration or filtration of runoff modifies baseflow and runoff temps (+ or - or no change, relative to the land use baseline)
- *Stream Corridor* Effect: reflects the *current* presence or absence of riparian/floodplain cover along the corridor (+ or -)
- *Corridor BMP* Effect: Whether the installation of a new BMP in the corridor from influences stream temps, relative to the historical corridor baseline. (+ or -)
- *Riverine/Reservoir* Effect: the increase in stream temp as it moves from headwaters thru rivers and is warmed by reservoirs and impoundments along the way, until it ultimately reaches head of tide (+).

To better account for the multiple factors that influence stream temperature, and the multiple pathways through which BMPs might impact stream temperature, the group also developed an accompanying conceptual model:



Next, the group developed an eight-bin classification system for evaluating the impacts of BMPs on water temperature, based on available monitoring and engineering and hydrologic considerations.

1. Known Heaters: Upland BMPs that have been shown to increase downstream temperatures due to surface ponding via detention or retention of runoff, to a depth of 10 feet. Examples include wet ponds, created wetlands, dry extended detention ponds, farm ponds, reservoirs, and CAFO lagoons.

2. Suspected Heaters*:* These BMPs have some, but not all, of the characteristics of known heaters, but have not been well studied from a temperature standpoint. Examples include sand filters, underground vaults and manufactured treatment devices (MTDs) that have closed bottoms and short runoff detention times.

3. Shaders*:* Upland or corridor forestry practices that maintain or increase forest canopy/forest cover after 10-15 years. Upland practices include tree planting, tree pits, foundation planters, which exert the greatest cooling effect when they occur over impervious cover. Corridor BMPs include riparian forest buffers and some forms of floodplain restoration.

4. Shade Removers: Land development activities, farming and drainage practices that remove riparian forests from the stream corridor, relative to the historic baseline year. Examples may include some forms of stream channel restoration involving extensive tree clearing, and construction of new land development. Other potential examples include "improved" urban and agricultural drainage, such as grass channels, ditches and swales.

5. Known Coolers: These BMPs are designed to shift a large fraction of surface runoff back into shallow groundwater, where it may reside for several days before reaching the headwater stream network. Good examples include infiltration and bioretention practices that lack underdrains, and level spreaders/vegetated filter strips.

6. Suspected Coolers*:* These urban BMPs also rely on LID practices such as infiltration, permeable pavement, dry swales and bioretention, but are located in tight soils, and therefore require underdrains. Other suspected coolers might include green roofs and floating treatment wetlands?

7. Thermally Neutral: A range of urban of and agricultural practices that do not appear to have much potential to change downstream temps. On the urban side, these include street and storm drain cleaning, urban nutrient management plans and IDDE. On the agriculture side, this might include agricultural nutrient management and various tillage and cropping practices.

8. Uncertain or Unknown: Practices that may increase or decrease temperature via multiple mechanisms and the net impact is uncertain. This is the category for all the BMPs that lack research or monitoring data to gauge their temperature impact. Given how many different BMPs exist in the Bay restoration effort, quite a few may fall into the unknown or uncertain category. The research focus should be on BMPs that treat a large watershed acreage.

Lastly, the group discussed some analytical issues in regard to the cumulative temperature impacts of BMPs in the watershed. They include the need to select which land use/BMP "year" will define the watershed temperature baseline, against which future warming due to climate change will be measured (2020?).

The cumulative impact of BMP on stream temperature can be expressed as the relative fraction of ("cool" BMPs * treated BMP acres) vs. ("heater" BMPs * treated BMP acres). The treated acres for each BMP category can be determined from CBWM inputs.
Two scenarios are of particular interest.

- The first is whether historic BMP implementation from 1970 to 2020 has cumulatively increased, decreased or has had no impact on stream temperatures discharged to the Bay.

- The second is whether a different mix of BMPs implemented in future years could potentially mitigate stream warming caused by climate change post-2020 and/or compensate for any heating by historic BMPs prior to 2020.

D. Synthesis

Most of the attention devoted to the impact of climate change on stormwater BMP performance has focused on more intense extreme rainfall events, and not as much has been paid on the potential to mitigate rising stream temperatures. Some recent resources on adapting stormwater BMPs to be more resilient to extreme rainfall in terms of their performance and design life include Wood (2020a, 2020b and 2021) and Miro et al (2021).

The increased attention on stream warming issues is most welcome given the difficulties of managing stormwater in cold-water watersheds and making habitat restoration projects more sustainable in the face of rising water temperatures in the Bay watershed.

Ding and Elmore (2015) noted that the rise in stream temperatures in the Bay watershed over the last 30 years cannot be fully explained by the corresponding increase in air temperatures over the same time period. This suggests that other landscape factors, such as some BMPs and the drainage/stream channels, may also contribute to stream warming in the Bay watershed.

Table 1 shows which types of BMPs fall into the temperature classification system and provides a comparative summary of the strength of the available research and the strength and direction of their effect on stream temperature, resulting from impacts on baseflow, runoff and groundwater temperature. Although there are other pathways through which these BMPs may impact water temperature, we found the most evidence around these four mechanisms. It also addresses any lag time needed for the temperature impact to occur, and whether that impact can be enhanced (cooling) or mitigated (warming).

Table 1: Initial classification of BMPs based on ability to influence stream and sub watershed temperatures

Category	**BMP types**	**Available research**	**Strength of BMP temp effect**			**Lag Time to Change Temp?**	**Can Impact be Enhanced or Mitigated?**
			Baseflow	**Runoff**	**G/W**		
Known Heaters	Wet ponds, created wetlands, dry ED ponds, farm ponds, CAFO lagoon	Strong	+++	++	?	None	Limited ability to mitigate, unless deeper than 10 ft
Suspected Heaters	Sand filters, MTDs,	Weak	++	+	-	None	Limited ability to mitigate
Shaders/ Interceptors	Upland and stream corridor forestry practices. Ag and urban forest buffers	Strong	- -	?	?	10 to 15 yrs	Enhanced by practices that accelerate tree canopy
Shade Removers	Land clearing, some channel restoration practices, open channels ag ditches	Weak	++	+	?	None, unless the site is reforested	Can be mitigated in headwater streams (e.g., forest buffer)
Known Coolers	Bioretention, porous pavement, infiltration, w/o underdrains	Strong	-	-	-	Weeks	Limited ability to enhance w/ urban soils
Suspected Coolers	LID practices w/ under-drains, floodplain habitat restoration	Weak	-	-	-	Hours	Need more data about GW & hyporheic exchange
Uncertain/ Unknown	Stream and floodplain restoration, Ag practices, Wetlands restoration	Weak	??	??	??	??	N/A
Thermally Neutral	Street cleaning, ag & urban NMPs, IDDE	Weak	?	?	?	??	No evident mechanism to change temps

Known and Suspected Heaters

Many urban BMPs used historically have been shown to induce stream warming, particularly those built from 1970 to 2010. These include wet and dry stormwater ponds, which have been shown to increase baseflow and runoff temps in multiple studies (Galli, 1990; Schueler, 2000; Jones & Hunt, 2010; and UNHSC, 2010). Monitoring also indicates that created stormwater wetlands increase downstream baseflow and runoff temps. In general, the magnitude of the temperature increase for stormwater ponds ranges from 2 to 10 degrees F above the local land use baseline.

Although not much monitoring data is available, it is likely that other shallow ponds exposed to sunlight have the same heating effect, such as CAFO lagoons and farm ponds. While stormwater ponds were extremely common before 2010, they are not widely used today, and are often restricted or prohibited in cold-water watersheds.

Known and Suspected Coolers

Many LID practices such as infiltration, bioretention and porous pavement appear to have some capability to cool runoff temperatures, depending on how much surface runoff is diverted into the soil/groundwater and how long it resides there. The key engineering variable appears to be the underground runoff residence time. Runoff that enters LID practices without underdrains make take many days or even weeks before they reach the headwater stream network.

In these cases, limited research suggests that the cooling effect can range from 2 to 5 degrees F, depending on underlying soils and hydro-geological conditions. Both monitoring and modeling research indicate that bioretention areas and vegetated filter strips have the capability to cool runoff that has been heated by the contributing pavement treated by the BMP (Jones, 2008; UNHSC, 2010; Winston et al., 2009; and Long & Dymond, 2013).

The cooling effect, however, was not great enough to meet cold-water temperature standards at either the site or sub-watershed scale (Jones, 2008 and Chen et al., 2020). This suggests that even the best LID practices cannot act like refrigerators – they can prevent further BMP warming, but generally cannot compensate for the land use effect on stream temperatures.

However, the majority (~90%) of LID practices are designed with underdrains to overcome soil constraints on infiltration. The underdrains reduce runoff residence times to a few hours to a day or so for most storm events, which sharply reduces their cooling potential (Selbig & Beun, 2018). More research is needed to see whether “surface” LID practices such as permeable pavement and green roofs have the potential to mitigate the temperature increases caused by the impervious surfaces they replace.

Shaders and Shade Removers

Stream corridor (riparian) forestry practices. Extensive research supports the role of riparian forests in cooling streams. Forested reaches have cooler maximum water temperatures and less temperature variation than non-forested reaches (Malcolm et al., 2008, Bowler et al., 2012, Turunen et al., 2021), and shade removal increases stream temperature (Nelson and Palmer, 2007). Riparian forests cool streams by providing shade that directly reduces solar radiation reaching streams. Abdi et al. (2020) found that by diminishing shortwave radiation to streams, riparian forests could reduce average river temperatures by 3.6° C. Simulations of mature forest also generated an 80% reduction in heat gains from shortwave radiation and a 48%reduction from young open forest (Wondzell et al., 2019).

Modeling has also suggested that both riparian and floodplain forests can cool ambient air temperatures and stream temperatures (Abdi et al., 2020), with another study demonstrating that shade and evapotranspiration can reduce temperatures in ponds and streams (Sun et al., 2015). Tree evapotranspiration can lower ambient temperatures by as much as 6 degrees C, although this effect can vary with tree species, the size of leaves, and their stomatal aperture (Gkatsopoulos, 2017). However, it is also important to consider the relationship between evapotranspiration and streamflow levels, as reducing streamflow can further exacerbate increasing stream temperatures, especially when there is already low flow.

The correlation between stream flow and tree evapotranspiration has been studied for decades. Federer in 1973 reported that streamflow recessions proceeded more quickly with the onset of tree transpiration in the spring and slowed with leaf drop in the fall. However, Dawson and Elheringer (1991) found that mature deep-rooted riparian zone trees do not use groundwater flow into streams as their primary water source. They observed that it is primarily younger more shallow rooted trees and herbaceous riparian vegetation whose transpiration affect streamflow.

Taken together, this suggests that while newly-planted buffers may reduce streamflow and potentially increase water temperature in low-flow situations, over the long-term, a mature buffer will provide a substantial net cooling benefit. Forests can transpire more water than most other cover types, but also have higher infiltration rates that aid groundwater recharge important for summer low flows. The net effect is not readily quantified but in the well-watered East, the potential for groundwater recharge is significant. Monitoring of infiltration rates of newly planting buffers in Maryland found small but significant increases in rates within 15 years.

Riparian forests have the greatest cooling effect in smaller headwater streams. In mid-order streams where there are wider channels and greater thermal inertia, riparian forests do not have as strong of an effect (Turunen et al., 2021). The type and structure of riparian forest cover can also influence stream cooling, with one study finding greater cooling benefits from dense conifer plantations than deciduous woodlands (Dugdale et al., 2018). For practices that remove shade, the obvious mitigation technique is to avoid removing trees where possible, especially mature trees that are directly shading streams.

In terms of the space and time needed to generate impacts on stream temperature, one study found that only 300 m of seminatural riparian vegetation in a headwater stream was needed to generate 1°C of cooling in the summer (Ryan et al., 2013), while another found that 1 km of riparian forests could reduce temperature by 1.5°C (Stanford et al., 2019). Newly planted trees will not provide any of these benefits immediately, but will grow as the trees do. Recent analysis by Iris Allen (MD DNR Forest Service) suggests that newly planted trees in the Chesapeake Bay Watershed require up to 15 years to generate enough canopy to be fully detected by aerial imagery, at which point, the trees would also provide significant shading benefits.

Stream temperature monitoring of newly planted buffers in Maryland found significant reductions in maximum daily temperatures during the summer after 15 years, confirming the temperature benefits after tree canopy closure, even though trees were not yet fully mature. These results confirm the value of expanding riparian reforestation to ameliorate temperature stressors and potentially reconnect isolated populations of cold-water species. However, the time lag needed for young trees to grow to crown closure emphasizes the need to conserve existing forests that are already providing valuable shading and stream health benefits.

Upland forestry practices. There is not as much research available about the stream temperature benefits of upland forestry practices. However, some research suggests that increased upstream shading reduces mean water temperature by cooling soils and impervious surfaces, with greater simulated benefits of cooling impervious surfaces, due to the fact that they store more heat and generate more runoff than pervious surfaces (Ketabchy et al., 2019).

When considering the implications of upland shade removal, in cases where riparian forests are maintained, one study found that upland forest harvesting had limited adverse effects on stream temperature, even with buffers that are only 10m wide (Clinton, 2011). However, another study found that when harvest had smaller buffers and less overall canopy retention, there was greater daily stream temperature fluctuations (Witt et al., 2016). This suggests maintaining larger buffers and more upland canopy can help minimize the stream temperature implications of upland forest harvesting. At the same time, when upland forest is removed and converted to development, there can be significant implications for water temperature. Built surfaces can increase the temperature of runoff due to their tendency to absorb more thermal energy than many natural surfaces (Janke et al., 2013).

Urban tree planting and urban forestry practices are increasing throughout the watershed. We expect these efforts will continue to grow with various state, regional, and national initiatives to plant more trees, with a particular emphasis on growing tree canopy in underserved communities.

Uncertain or Unknown Practices

This is the category for all the BMPs that lack research or monitoring data to gauge their temperature impact.

Stream and Floodplain Restoration. There has been quite a bit of debate about the impact of stream restoration projects on downstream temperatures. A recent review of the rather scanty literature on the topic can be found in Wood and Schueler (2020). Some practices, such as certain kinds of floodplain and wetland restoration appear to be able to cool baseflow temperatures, at least to some degree.

On the other hand, abundant evidence exists that stream channel restoration projects that require extensive riparian tree clearing can induce stream warming, at least until such time as the post-project reforestation matures. A series of best practices for design and construction of stream/floodplain restoration practices has been developed to minimize the unintended consequences of this class of projects (Wood and Schueler, 2020).

Agricultural BMPs: Forest buffers are a key agricultural practice that are known to provide cooling benefits. However, less is known about the water temperature impacts of other agricultural land management BMPs. Some agricultural BMPs, including saturated buffers for drainage systems, horse and livestock pasture management, and high residue tillage management systems, are known to improve surface vegetative cover and water infiltration, which may provide downstream cooling benefits by diverting surface runoff into the soil profile and to groundwater. Likewise, although grass buffers do not provide the shade function of trees, they can provide infiltration benefits. The conversion of agricultural row crop fields to pasture, forest, or to open space represent land use BMPs with possible water temperature impacts.

There is uncertainty about the extent to which these agricultural practices impact water temperature, especially in comparison with the broader effects of non-agricultural land use on water temperature. Nonetheless, considering the prevalence of agricultural lands in the watershed and the relatively large number of acres implementing these practices, the cumulative impacts may be significant. Further research into the water temperature impacts of these agricultural BMPs is merited.

Wetlands BMPs:

Wetlands act like a sponge, soaking up stormwater and dampening storm surges. Wetlands in the Chesapeake Bay watershed develop into familiar forms that include marshes, swamps and bogs dependent on the level, frequency, and duration of water inundation. Multiple studies have examined the potential heater aspects of created wetlands (Galli, 1990; Schueler, 2000; Jones & Hunt, 2010; and UNHSC, 2010). However, wetlands also have cooling potential. Wetlands are usually comprised of suites of vegetative cover types with varying evapotranspiration rates. Gleick (2000) reported that because of high soil moisture, surface roughness, and large areas of foliage, wetlands are usually characterized by higher evaporation rates in relation to an open water surface. Surface temperatures at wetlands with open water were up to 5.1 degrees C cooler than a crop field during the daytime.

Stannard et al.(2013) compared the evapotranspiration rates of two wetland sites selected to typify vegetation communities and hydrologic conditions with an alfalfa field and a pasture. Alfalfa had the highest annual ET due to its leaf structure, providing multiple layers and flat surfaces for efficient evaporation to occur, whereas bulrush is more grass-like with a thin, smooth structure and single needles side by side that are not conducive for efficient evaporation. However, the wetlands had higher annual ET than the pasture. This suggests that vegetation types and structure play a significant role in determining ET and the potential cooling benefits of wetlands. ET expectations would be lower for a wetland with a high percentage of open water as opposed to a high percentage of mixed vegetation.

Forested wetlands likely provide additional cooling benefits due to the amount of evapotranspiration that takes place in forested areas compared to wetlands without trees. Large trees can transpire as much as 100 gallons of water a day (Gkatsopoulos, 2017), but older trees do not cycle as much water as younger trees (Dawson & Elheringer, 1991). This would make a case for retaining older trees along waterways because of their more limited uptake of water from within the wetland system. The size of leaves, and their stomatal aperture also control transpiration which indicates that the selection of species used in created forested wetlands is important (Gkatsopoulos, 2017).

Although research does present evidence that wetlands have the potential to have a cooling effect, future research may present a more exact picture of the features of wetlands that provide cooling benefits and whether wetlands can help cool stream water temperatures. Given the significant variability in created wetlands, there is still uncertainty about whether these BMPs generate a net cooling or heating effect. However, we suspect that that the restoration, enhancement and rehabilitation of existing wetlands is likely to have a net cooling effect to the extent these BMPs help increase ET by enhancing vegetation abundance and diversity within existing wetlands, reducing the amount of open water.

Historic BMP implementation in the Chesapeake Bay Watershed

Estimates of historic BMP implementation using the Chesapeake Assessment Scenario Tool (CAST), reveals that watershed-wide, there has been substantially greater implementation of “heater” BMPs as compared with “cooler” BMPs. In many years, there has been approximately three times as much implementation of heaters as coolers. There has been comparatively less implementation of stream restoration practices.

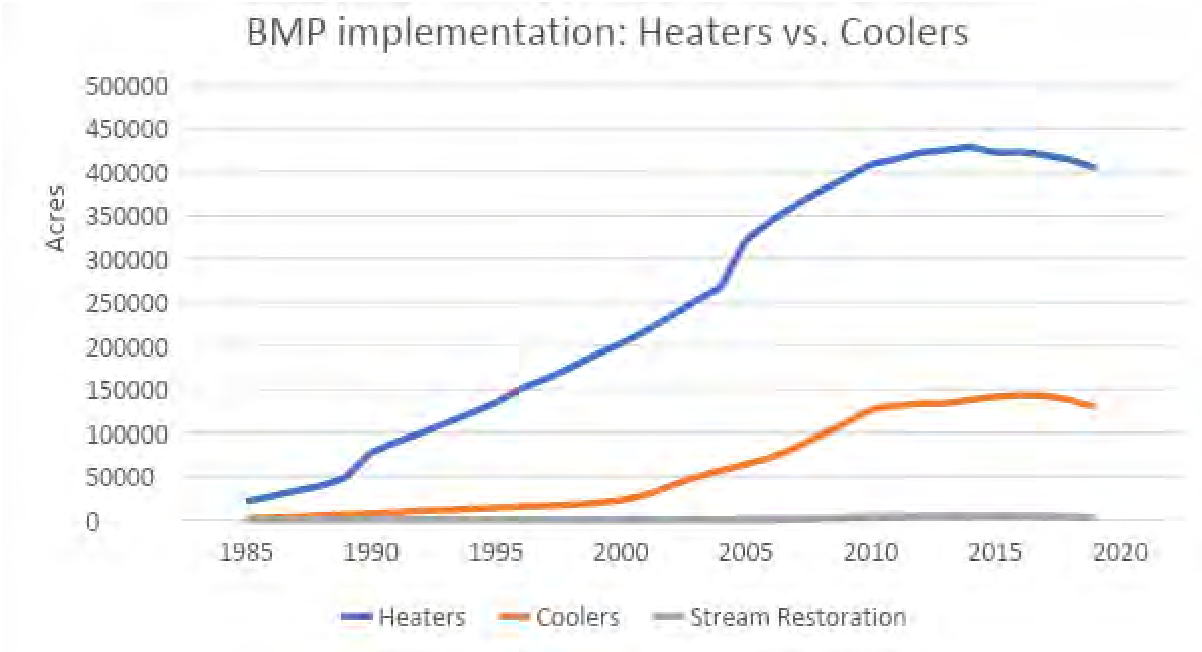


Figure 1: Historic implementation of heater and cooler BMPs in the Chesapeake Bay Watershed. Refer to Appendix A for a full list of BMPs included in each category.

There is still significant uncertainty about the temperature impacts of agricultural BMPs. However, even looking at a subset of practices that have the potential to influence water temperature by increasing infiltration reveals the magnitude at which these practices these are implemented and underscores the importance of further considering their cumulative impacts.

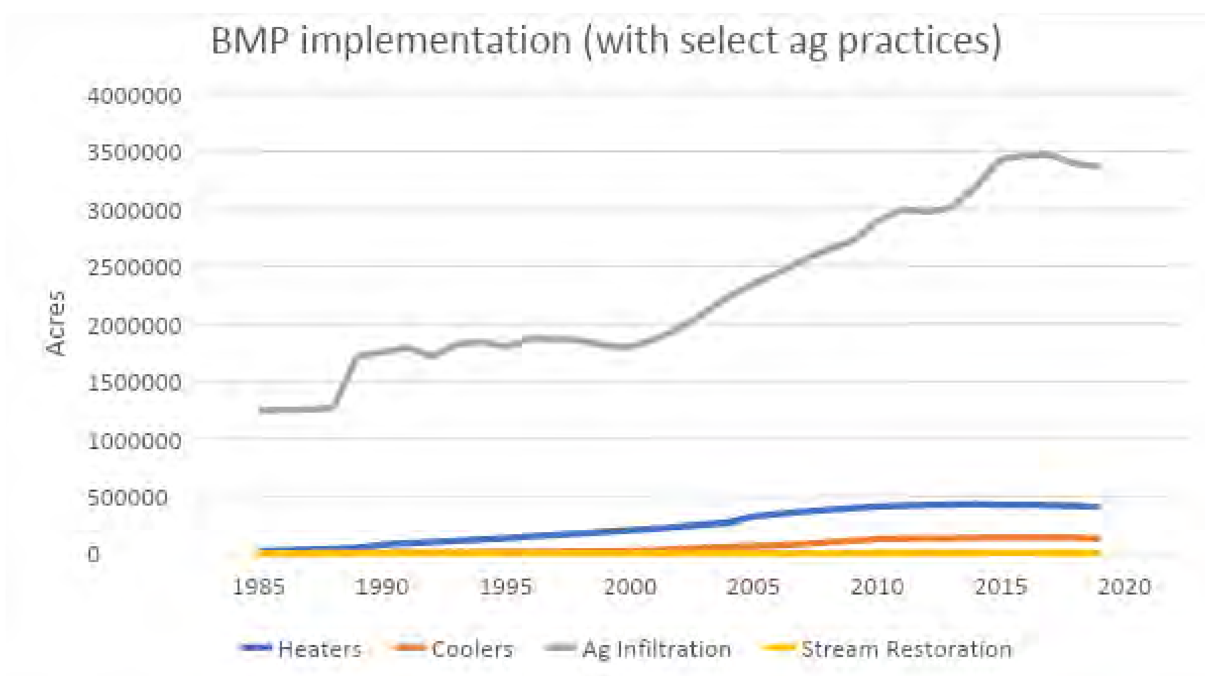


Figure 2: Historic implementation of BMPs with Ag BMPs that may influence temperature. Refer to Appendix A for a full list of BMPs included in each category.

E. Evaluation

How good is the data?

While significant gaps remain, there is enough data for urban and forestry practices to get a general sense of their impact of historic and future BMPs on stream temperatures in the watershed. Our level of certainty in categorizing BMPs as heaters and coolers is built into classification system, where we identify practices in which we have lower confidence as suspected heaters and coolers. Although we can hypothesize about the mechanisms through which some agricultural BMPs may influence water temperature, at this time, there is insufficient existing research demonstrating the stream temperature impacts of agricultural and habitat restoration practices. We do not expect that our level of certainty will change significantly in the coming 3-5 years given the incremental nature of scientific research.

In all cases, we lack enough data to model past and future changes in stream temperatures at the scale of the Bay watershed, especially in response to future management and BMP implementation scenarios.

What do we know about the watershed impact of BMPs on stream temperatures?

On the urban side, stormwater BMPs have a mixed effect, but historically, we have installed more "heaters" than "coolers", at least in terms of treated acreage. When combined with increased upland and corridor tree clearing and the construction of urban ditches and swales to convey stormwater runoff, it is likely that that the urban sector has had the net effect of further exacerbating stream warming, beyond the heat island/land use effect associated with urban impervious cover.

Forestry tree planting BMPs, especially in the riparian corridor, can effectively lower stream temperatures once established. These practices may be particularly valuable in lowering maximum temperatures in the summer, when relatively high temperatures put aquatic biota at particular risk. In urban areas, the trend toward more widespread use of LID practices suggests that the BMP effect on downstream temperatures could be significantly reduced in the future. As noted earlier, however, stormwater BMPs are not refrigerators, and no evidence exists that they can compensate for the predominant impact of urban land use on stream warming. Additional synthesis efforts are needed to further evaluate the relative role of BMPs in influencing water temperature relative to broader land use and climatic trends.

What we can take action on now based on what we know:

Some potential management actions include:

- Reinforce the need for state and local stormwater permitting agencies to prevent BMP warming in cold-water watersheds by restricting or prohibiting the use of known heaters (and possibly also suspected heaters, as well).

- Do more training and outreach to support best practices to avoid unintended consequences associated with future stream/floodplain restoration projects.

- Consider dam/pond removal and associated floodplain restoration projects in rural watersheds as a potential temperature mitigation for cold-water fisheries on a localized basis.

- Update urban and forestry BMP plant lists to make sure the species we are planting are appropriate for the future hardiness zones in our warming watershed. Encourage diversity in plant selection to hedge against potential losses to invasive pests and plants. Consider large and tall trees where space permits to maximize benefits from tree planting spaces.

What more needs to be done before the workshop?

The following actions could help evaluate management scenarios and appear to be doable over the summer months if someone volunteers for them.

- Add more research (if it exists) on the temperature impacts of agricultural and habitat restoration practices located in upland areas and the stream corridor.

- Check out the International Stormwater BMP pollutant removal database to see if there are any more urban BMP temperature "efficiency" data to analyze.

- Investigate potential overlays with other datasets to evaluate where there are opportunities for BMPs to provide additional cooling benefits. For example, calculating the total headwater stream mileage in cold-water portions of the Bay watershed that potentially could be reforested.

F. Bibliography

Abdi, R., Endreny, T. & Nowak, D. (2020). A model to integrate urban river thermal cooling in river restoration. *Journal of Environmental Management*, *258,* 110023.

Bowler, D., Mant, R., Orr, H., Hannah, D., & Pullin S. (2012). What are the effects of wooded riparian zones on stream temperature? *Environmental Evidence, 1*(1), 1-9.

Chen, H., Hodges, C. & Dymond, R. (2020). Modeling watershed-wide bioretention stormwater retrofits to achieve thermal pollution mitigation. *JAWRA Journal of the American Water Resources Association*, *57*(1).

Clinton, B. (2011). Stream water responses to timber harvest: riparian buffer width effectiveness. *Forest Ecology and Management, 261*(6), 979-988.

Dawson, T., & Ehleringer, J. (1991). Streamside trees that do not use stream water. *Nature, 350*(6316), 335-337.

Ding, H., & Elmore, A. (2015). Spatio-temporal patterns in water surface temperature from Landsat time series data in the Chesapeake Bay, USA. *Remote Sensing of Environment, 168,* 335-348.

Dugdale, S., Malcolm, I., Kantola, K., & Hannah, D. (2018). Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange processes. *Science of The Total Environment*, *610,* 1375-1389.

Federer, C. (1973). Forest transpiration greatly speeds streamflow recession. *Water Resources Research, 9*(6), 1599-1604.

Galli, F.J. (1990). Thermal impacts associated with urbanization and stormwater best management practices in Maryland. Report prepared for Maryland Department of Environment. Anacostia Restoration Team. Metropolitan Washington Council of Governments.

Gkatsopoulos, P. (2017). A methodology for calculating cooling from vegetation evapotranspiration for use in urban space microclimate simulations. *Procedia Environmental Sciences, 38*, 477-484.

Gleick P.H. (2000). Water: the potential consequences of climate variability and change for the water resources of the United States. Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA.

Hinson, K., Friedrichs, M., St-Laurent, P., Da, F., & Najjar, R. (2021). Extent and causes of Chesapeake Bay warming. *Journal of the American Water Resources Association*.

Janke, B., Herb, W., Mohseni, O., & Stefan, H. (2013). Case study of simulation of heat export by rainfall runoff from a small urban watershed using MINUHET. *Journal of Hydrologic Engineerin*g. *18*(8), 995-1006.

Jones, M. (2008). Effect of urban stormwater BMPs on runoff temperatures in trout sensitive watersheds. NCSU. Dept. of Biological and Agricultural Engineering

Jones, M., & Hunt, W. (2010). Effect of stormwater wetlands and wet ponds on runoff temperature in trout sensitive watersheds. *J. of Irrigation and Drainage Engineering*, *136*(9), 656-661.

Ketabchy, M., Sample, D., Wynn-Thompson, T., & Yazdi. M. (2019). Simulation of watershed-scale practices for mitigating stream thermal pollution due to urbanization. *Science of the Total Environment*, *671*, 215-231.

Long, D., & Dymond, R. (2013). Thermal pollution mitigation in cold-water stream watersheds using bioretention. *JAWRA Journal of the American Water Resources Association, 50(4).*

Malcolm, I., Soulsby, C., Hannah, D., Bacon, P., Youngson, A., & Tetzlaff, D. (2008). The influence of riparian woodland on stream temperatures: implications for the performance of juvenile salmonids. *Hydrological Processes, 22(7),* 968–979. https://doi.org/10.1002/hyp.6996

Miro, M., DeGaetano, A., Lopez-Cantu, T., Samaras, C., Webber M., & Grocholski, K. (2021). Piloting the development of future projected intensity, duration frequency (IDF) curves – technical report on data, metrics, and IDF curves for the Chesapeake Bay watershed. Rand Corporation.

Nelson, K. C., & Palmer, M. A. (2007). Stream temperature surges under urbanization and climate change: Data, models, and responses 1. *JAWRA journal of the American water resources association*, *43*(2), 440-452.

Paraszcuk, W. Changes in Stormwater Thermal Loads Due to Bioretention Cells, 2021 Masters Thesis, https://vtechworks.lib.vt.edu.

Ryan, D., Yearsley, J., & Kelly-Quinn, M. (2013). Quantifying the effect of semi-natural riparian cover on stream temperatures: implications for salmonid habitat management. *Fisheries Management and Ecology*, *20*(6), 494–507. https://doi.org/10.1111/fme.12038

Schueler, T. (2000). The environmental impacts of stormwater ponds. Article 79 in the *Practice of Watershed Protection*. Center for Watershed Protection. Ellicott City, MD.

Selbig, W., & Buer, N. (2018). Hydraulic, water quality and temperature performance of three types of permeable pavement under high sediment loading conditions. USGS Scientific Investigation Report No. 2018-5037.

Stanford, B., Holl, K., Herbst D., & Zavaleta, E. 2019. In-stream habitat and macroinvertebrate responses to riparian corridor length in rangeland streams. *Restoration Ecology*, *28*(1), 173–184. https://doi.org/10.1111/rec.13029

Stannard, D.., Gannett, M., Polette, D., Cameron, J., Waibel, M., & Spears, J., 2013, Evapotranspiration from marsh and open-water sites at Upper Klamath Lake, Oregon, 2008–2010: U.S. Geological Survey Scientific Investigations Report 2013–5014.

Sun, N., Yearsley, J., Voisin, N., & Lettenmaier, D. (2015). A spatially distributed model for the assessment of land use impacts on stream temperature in small urban watersheds. *Hydrological Processes, 29*(10), 2331-2345.

Turunen, J., Elbrecht, V., Steinke, D., & Aroviita. J. (2021). Riparian forests can mitigate warming and ecological degradation of agricultural headwater streams. *Freshwater Biology*, *66*(4), 785-798.

University of New Hampshire Stormwater Center (UNHSC). (2010). Examination of thermal impacts from stormwater best management practices.

Winston, R., Hunt, W., & Lord, W. (2011). Thermal mitigation of urban stormwater by level spreader-vegetative filter strips. *Journal of Environmental Engineering 137*(8), 707-716.

Witt, E., Barton, C., Stringer, J., Kolka, R., & Cherry, M. (2016). Influence of variable streamside management zone configurations on water quality after forest harvest. *Journal of Forestry*, *114*(1), 41-51.

Wondzell, S., Diabat, M., & Haggerty, R. (2019). What matters most: are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? *JAWRA Journal of the American Water Resources Association*, *55*(1), 116-132.

Wood, D. (2020a). Summary of survey results, current management and future needs for addressing climate change impacts on stormwater management. Report prepared for Urban Stormwater Work Group. Chesapeake Bay Program. Chesapeake Stormwater Network. Ellicott City, MD

Wood, D. (2020b). Review of recent research on climate projections for the Chesapeake Bay watershed. Report prepared for Urban Stormwater Work Group. Chesapeake Bay Program. Chesapeake Stormwater Network. Ellicott City, MD

Wood, D. & Schueler, T. (2020). Consensus recommendations to improve Protocols 2 and 3 for defining stream restoration pollutant removal credits. Approved by Water Quality Goal Implementation Team of Chesapeake Bay Program. (Section 7 and Appendix F)

Wood, D. (2021). Vulnerability analysis and resilient design considerations for stormwater BMPs. Report prepared for Urban Stormwater Work Group. Chesapeake Bay Program. Chesapeake Stormwater Network. Ellicott City, MD.

Appendix A: BMPs included in the historic BMP implementation analysis

Heaters (includes known and suspected heaters)

- Dry ponds
- Extended dry ponds
- Floating treatment wetlands
- Wet ponds & wetlands
- Vegetated open channel

Coolers (includes known coolers, suspected coolers, and shaders)

- Agricultural tree planting
- Bioretention
- Bioswale
- Forest buffers
- Forest buffers on fenced pasture corridor
- Impervious surface reduction
- Infiltration practices
- Permeable pavement
- Urban filter strips
- Urban forest buffers
- Urban forest planting
- Urban tree planting
- Wetland enhancement and rehabilitation
- Wetlands restoration

Agricultural infiltration practices (included in the unknown/uncertain category)

- Conservation tillage
- Grass buffers
- Grass buffers on fenced pasture corridor
- High residue tillage
- Horse pasture management
- Land retirement
- Pasture alternative watering
- Prescribed grazing

Stream restoration practices

**Note: Practices converted from linear feet to acres assuming a 100 ft average width*

- Non-urban stream restoration
- Urban stream restoration

Appendix L
Synthesis Element 9: Synthesis of Information Supporting Development of and Options for a Tidal Bay Water Temperature Change Indicator

Synthesis Element 9: Synthesis of Information Supporting Development of and Options for a Tidal Bay Water Temperature Change Indicator

Abstract

There is interest by the Chesapeake Bay Program (CBP) to develop a Tidal Bay Water Temperature Change Indicator to assess the effects of rising water temperatures related to ecological impacts in Chesapeake Bay. The Rising Water Temperature STAC Workshop effort offers the opportunity to bring together experts in habitats, fisheries, and climate change assessment to identify potential habitat and fisheries management applications for a Tidal Bay Water Temperature Change Indicator and discuss available data, spatial and temporal needs, and monitoring gaps in relation to identified applications. The synthesis findings by the tidal fish (#2) and submerged aquatic vegetation (#3) teams and feedback from the workshop participants will be used to help inform options for the Tidal Bay Water Temperature Change Indicator to be presented to the CBP Management Board.

This synthesis paper focused on reviewing the CBP climate change indicator work to date, compiling examples of temperature-related climate change indicators to provide insights on methods to track long-term trends, presenting examples and conceptual ideas of temperature change indicators connected to ecological impacts, and identifying the strengths and limitations of available water temperature data in Chesapeake Bay. The following highlights the main findings from the synthesis:

- Assessing physical water temperature change methods exist, but connecting these changes to ecological impacts (e.g., habitats, living resources) to inform management responses is lacking.
- To work towards a Tidal Bay Water Temperature Change Indicator that has management utility related to assessing ecological impacts and tracking management responses, we need input from experts managing these resources on their application needs to identify the spatial and temporal requirements for the indicator.
- There is no one single data source that will likely meet all the desired criteria (accuracy, spatial resolution, temporal extent) to address management questions related to their responses to rising Bay water temperatures on habitats and living resources.
- Given likely data limitations, a multi-data source approach could allow for a more robust indicator (e.g., combining satellite data and monitoring data).
- It will be important to consider indicator longevity (e.g., agreements with data providers, maintenance plan) to ensure reliability of the indicator for decision-making needs.

A. Contributors

Julie Reichert-Nguyen, National Oceanic Atmospheric Administration (NOAA), Bruce Vogt, NOAA; Mandy Bromilow, NOAA Affiliate; Ron Vogel, UMD for NOAA Satellite Service; Breck Sullivan, Chesapeake Research Consortium (CRC); Anissa Foster, NOAA-CRC Internship Program

B. Resources

The following resources were reviewed to inform workshop conversations related to the development of the Tidal Bay Water Temperature Change Indicator in connection with ecological impacts:

- 2018 CBP Climate Change Indicator Plan (Eastern Research Group, Inc. 2018)
- Climate Change Indicators on Chesapeake Progress
- 2021 CBP Prioritization of Climate Change Indicators Document
- Other Indicator and Trends Analysis Programs
    - Physical Change
        - United States Environmental Protection Agency (U.S. EPA) Climate Change Indicators (Mike Kolian, U.S. EPA)
        - Integrated trends analysis of Bay water temperature change (R. Murphy, University of Maryland Center for Environmental Science [UMCES], and J. Keisman, United States Geological Survey [USGS])
        - Indicator for the National Estuary Program extended to Chesapeake Bay (R. Vogel, NOAA, M. Craghan, U.S EPA, and M. Tomlinson, NOAA)
    - Physical Change in Connection with Ecological Impacts
        - Health Watersheds Assessment (Renee Thompson, USGS)
        - Forage Action Team seasonal warming indicator effort (Mandy Bromilow, NOAA Affiliate)
- Date Sources
    - In-Situ
        - CBP Long-term Monitoring Stations: 1985-present, Monthly
        - Chesapeake Bay Interpretive Buoy System (CBIBS): 2008-present, 5 buoys, 10-60 minute intervals
        - Chesapeake Biological Laboratory (CBL) pier: 1938-present
        - Thomas Point Lighthouse C-MAN station: 1985-present, hourly
    - Satellite
        - Multi-Satellite AVHRR: 2008-present, Daily, 1km - shorter record
        - Geo-Polar Blended: 2002-present, Daily, 5km - coarser spatial res
        - Landsat: 1982-present, Daily, 30m - less accurate
        - European Climate Change Initiative: 1981-2016, Daily, 5km - only avail to 2016

- Exploratory Analyses to Connect Water Temperature Data to Fish Impacts
  - Data needs and availability in relation to designated fish spawning grounds (S. Fadullon, NOAA-CRC intern)
  - Literature review on ecological-related indicators to inform conceptual ideas for the Tidal Bay Water Temperature Change Indicator (A. Foster, NOAA-CRC intern)

C. Approach

A Tidal Bay water temperature change indicator can be approached in different ways depending on the application need for the indicator and the management question being asked. Our synthesis approach was to look at information and data that could support the assessment of water temperature change in the Bay and begin evaluating considerations to connect these changes to impacts on living resources (e.g., fisheries) and habitat. During the synthesis evaluation, we focused on summarizing the temperature-related CBP climate change indicators to date, identifying examples of indicator methodologies related to assessing physical changes in water temperatures and options for connecting to ecological impacts, and evaluating relevant water temperature data sources, including an initial assessment of data strengths and limitations related to spatial and temporal coverage.

D. Synthesis

Introduction

The CBP is working towards developing indicators for all outcomes in the 2014 Chesapeake Bay Watershed Agreement[1] to track progress towards meeting respective goals. The Climate Resiliency Workgroup has been working on developing indicators for the Climate Monitoring and Assessment and Climate Adaptation outcomes under the Climate Resiliency Goal.

- **Climate Resiliency Goal:** Increase the resiliency of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure and communities, to withstand adverse impacts from changing environmental and climate conditions.
  - **Monitoring and Assessment Outcome:** Continually monitor and assess the trends and likely impacts of changing climatic and sea level conditions on the Chesapeake Bay ecosystem, including the effectiveness of restoration and protection policies, programs and projects.

  - **Adaptation Outcome:** Continually pursue, design and construct restoration and protection projects to enhance the resiliency of Bay and aquatic ecosystems from the impacts of coastal erosion, coastal flooding, more intense and more frequent storms and sea level rise.

[1] The 2014 Chesapeake Bay Watershed Agreement: www.chesapeakebay.net/what/what_guides_us/watershed_agreement

The climate change indicator implementation strategy for the Chesapeake Bay Program (Eastern Research Group, Inc. 2018) outlined the following needs: (1) define the indicator and its metrics, (2) have a data collection program in place, (3) select methods to transform the data into an indicator, (4) process the data, and (5) have an available indicator for the Chesapeake Bay. Bay Water Temperature was one of the proposed indicators that was identified by the Climate Resiliency Workgroup to develop. The Eastern Research Group formulated an initial vision for the Tidal Bay Water Temperature indicator, including identifying potential metrics involving satellite data (i.e., temperature trends over a period of record, spatially averaged over 1-km grid cells) and in-situ data, (i.e., single Bay-wide trend in line graph or trends for each sampling location in a map).

Additionally, the CBP climate change indicator implementation strategy identified the following ecological-related values to consider when developing the Tidal Bay Water Temperature Change Indicator: frequency and extent of harmful algal blooms, submerged aquatic vegetation composition, and fish population distributions. The plan also mentioned that warming water temperatures effects on ecosystems could lead to economic impacts to fishing and crabbing industries and recreation in the Chesapeake Bay. It also emphasized the relationship of air temperature as a primary driver of Bay water temperature change and how changes in stream temperature could also play a role in relation to water flow into the Bay. Recent research by Hinson et al. (accepted for publication) also demonstrated that water temperature in the mainstem of the Bay were driven by changes in air temperature followed by changes in ocean circulation.

The development of the CBP climate change indicator strategy led to a partnership with the U.S. EPA Climate Change Program where they clipped their national indicators for the Chesapeake Bay. This led to seven indicators that are now on Chesapeake Progress,[2] including average air temperature increases, change in high air temperature extremes, stream water temperature change, change in total precipitation, river flood frequency, river flood magnitude, and relative sea level rise.

While the seven indicators on Chesapeake Progress was a critical first step, these indicators only represent physical change occurring on a broad spatial and temporal scale. They are not currently structured to inform resilience actions at a project implementation scale, which is needed to address the Climate Resiliency Goal in the Chesapeake Bay Watershed Agreement.

[2] Chesapeake Progress Climate Change Indicators: www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment

During 2020-2021, the Climate Resiliency Workgroup built into their management strategy[3] the goal to connect the climate change indicators to clear management purposes related to the Chesapeake Bay Watershed Agreement's water quality, habitat, and living resources goals. The Climate Resiliency Workgroup agreed on a framework where the physical change would be expressed in connection with ecological and community impacts to help identify and inform needed resilience actions (Figure IX-1).

Figure IX-1. Climate Change Indicator Framework by the Chesapeake Bay Program's Climate Resiliency Workgroup.

Using this framework, the Climate Resiliency Workgroup with approval from the Management Board prioritized the development of a Tidal Bay Water Temperature Change Indicator in connection with water quality thresholds for fish and submerged aquatic vegetation (SAV) habitat to inform adaptive management.[4] The warming effects on fish and SAV outlined in the corresponding synthesis papers for this STAC workshop effort (synthesis papers #2 and #3, respectively) and the eventual identified management responses from the workshop could be used to inform how to structure the indicator or indicators for changes in bay water temperature related to ecological impacts with clearly identified management purposes. It will be important to consider the spatial and temporal scales needed to inform the specific management application that the indicator is being designed for.

The following sections summarize the existing temperature-related climate change indicators, other indicator efforts related to assessing long-term trends in Bay water temperature, and water temperature indicators that are structured in connection with fish impacts. These indicator examples and methodologies can help inform conversations in identifying options for the Tidal Bay Water Temperature Change Indicator in connection with ecological impacts from climate change. The remaining sections summarize the available water temperature data

[3]Climate Resiliency Workgroup Management Strategy: www.chesapeakebay.net/channel_files/24283/2021-2022_climate_mgt_strategy_final_submit_4-30-21_edit_6-8-21.pdf

[4] Prioritized climate change indicators approved by the CBP Management Board: www.chesapeakebay.net/channel_files/41939/list_of_climate_change_indicators_for_mgmt_board_discussion_final.pdf

sources and provides an initial assessment of the spatial and temporal strengths and limitations and presents a couple of exploratory analyses looking at connecting this data with assessing fish impacts and conceptual ideas related to fish habitat suitability.

WATER TEMPERATURE-RELEVANT CLIMATE CHANGE INDICATORS ON CHESAPEAKE PROGRESS

There are currently three temperature-related climate change indicators on Chesapeake Progress:[5] average air temperature increases, change in high air temperature extremes, and stream water temperature change. These indicators have been adapted from broader regional indicators by the U.S. EPA Climate Change Indicator program.[6] **While these indicators are focused in the watershed, they could provide insights on methodologies and possible visual representations for the Tidal Bay Water Temperature Change Indicator**. Detailed documentation on the methods and analyses for these indicators can be found on Chesapeake Progress. These indicators are briefly described below.

Average Air Temperature Increases

The Average Air Temperature Indicator (Figure IX-2) is derived from temperature measurements collected from land-based weather stations. It calculates annual temperature anomalies from 1901 to 2017 using the average temperature from a baseline period of 1901 to 2000. A gridded analysis averages climate data over climate regions across the U.S., with the slope of each temperature trend calculated from the annual anomalies by ordinary least-squares regression and then multiplied by 100 to obtain a rate of change per century.

---

[5] Chesapeake Bay Program Climate Change Indicators: www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment

[6] U.S. EPA Climate Change Indicators: www.epa.gov/climate-indicators

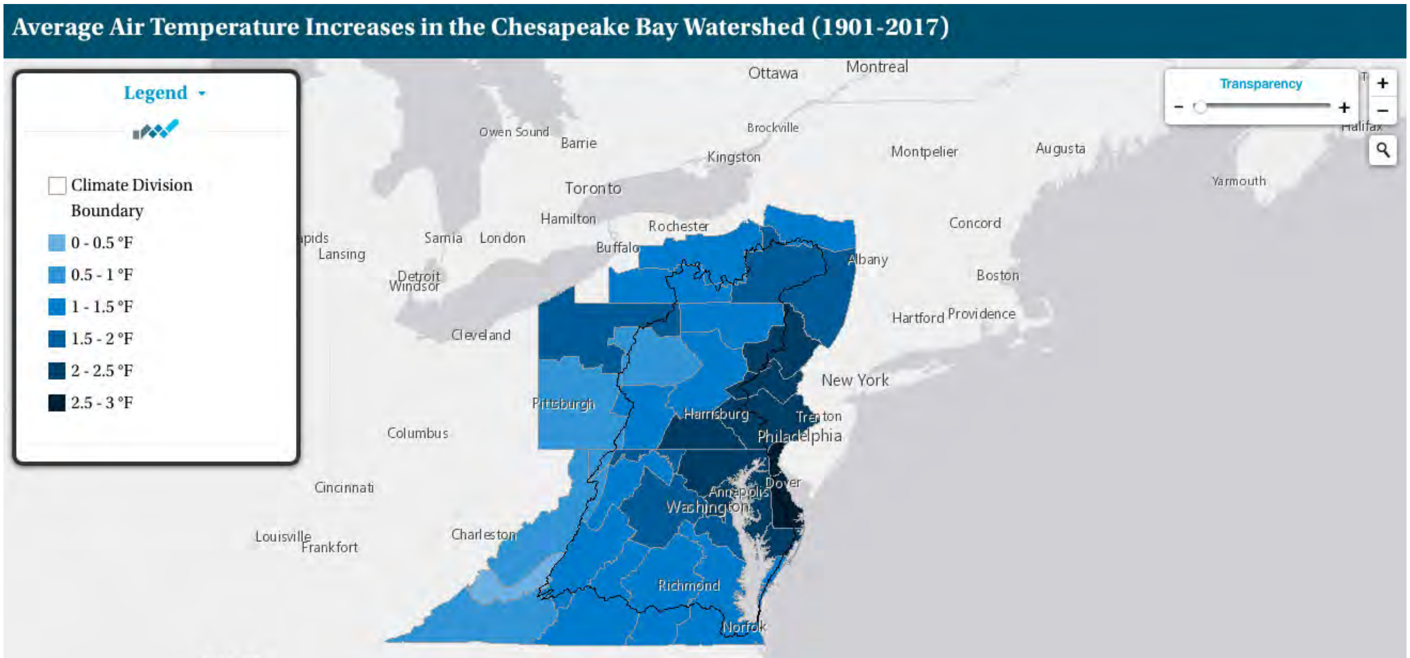


Figure IX-2. Climate change indicator showing the average air temperature increases in the Chesapeake Bay watershed in 2017 based on a baseline period of 1901-2000. Chesapeake Progress, www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment.

Change in High Air Temperature Extremes

The Change in High Air Temperature Extremes Indicator (Figure XI-3) also uses data from land-based weather stations. These data are compiled by the Global Historical Climatology Network, Daily edition (GHCN-Daily) overseen and maintained by NOAA. The method for this indicator calculates the 95th percentile daily maximum temperature of each station for the full time period and identifies exceedances above the 95th percentile (i.e., unusually hot days). Ordinary least-squares linear regression is used to determine the average rate of change over time in the number of > 95th percentile days. Regression coefficients for regressions significant at $p \leq 0.1$ are multiplied by the number of years in the analysis to estimate the total change in the number of annual > 95th percentile days over the full period record. Values, including zeros for insignificant trends, are mapped to show trends at each climate station.

Change in High Temperature Extremes in the Chesapeake Bay Watershed (1948-2017)

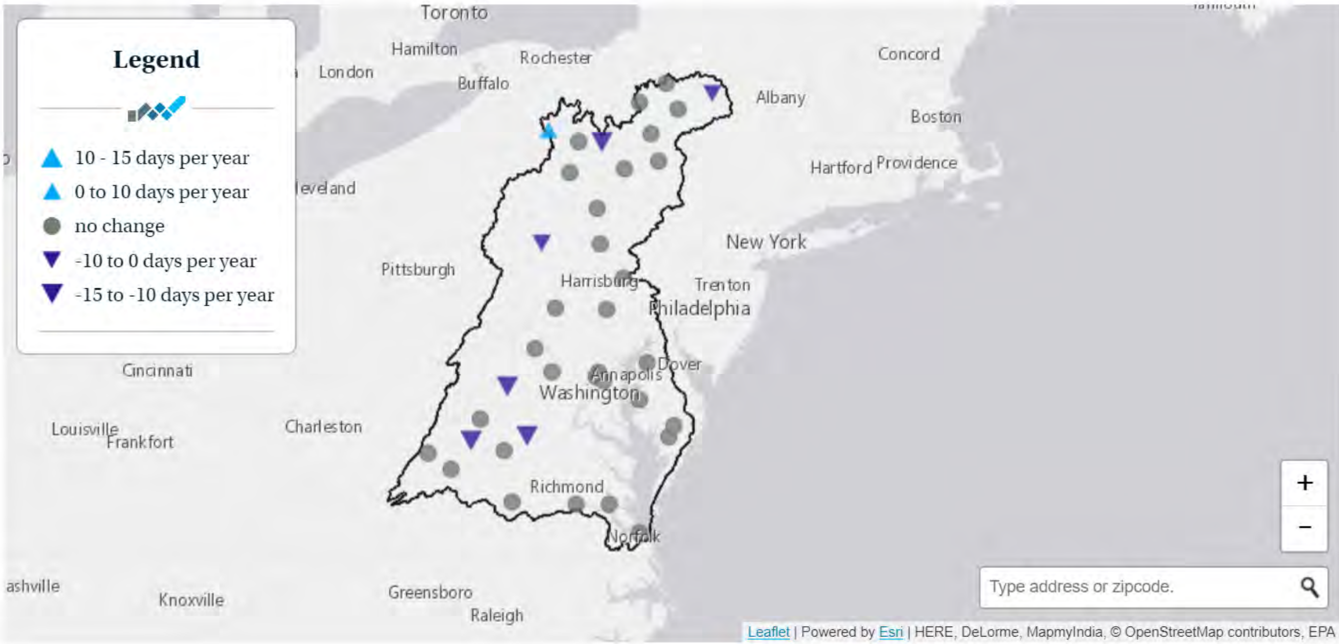


Figure IX-3. Climate change indicator showing the change in high temperature extremes in the Chesapeake Bay watershed in 2017 since 1948. Chesapeake Progress, www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment.

Stream Temperature Change

The Stream Water Temperature Change Indicator (Figure IX-4) uses data from the USGS stream gauge sites. Long-term monthly averages are calculated for each site and individual measurements are converted into anomalies (relative to the site-specific mean) to compare changes across sites. This indicator is currently not being updated given re-writing of data analysis and sharing protocols by USGS.

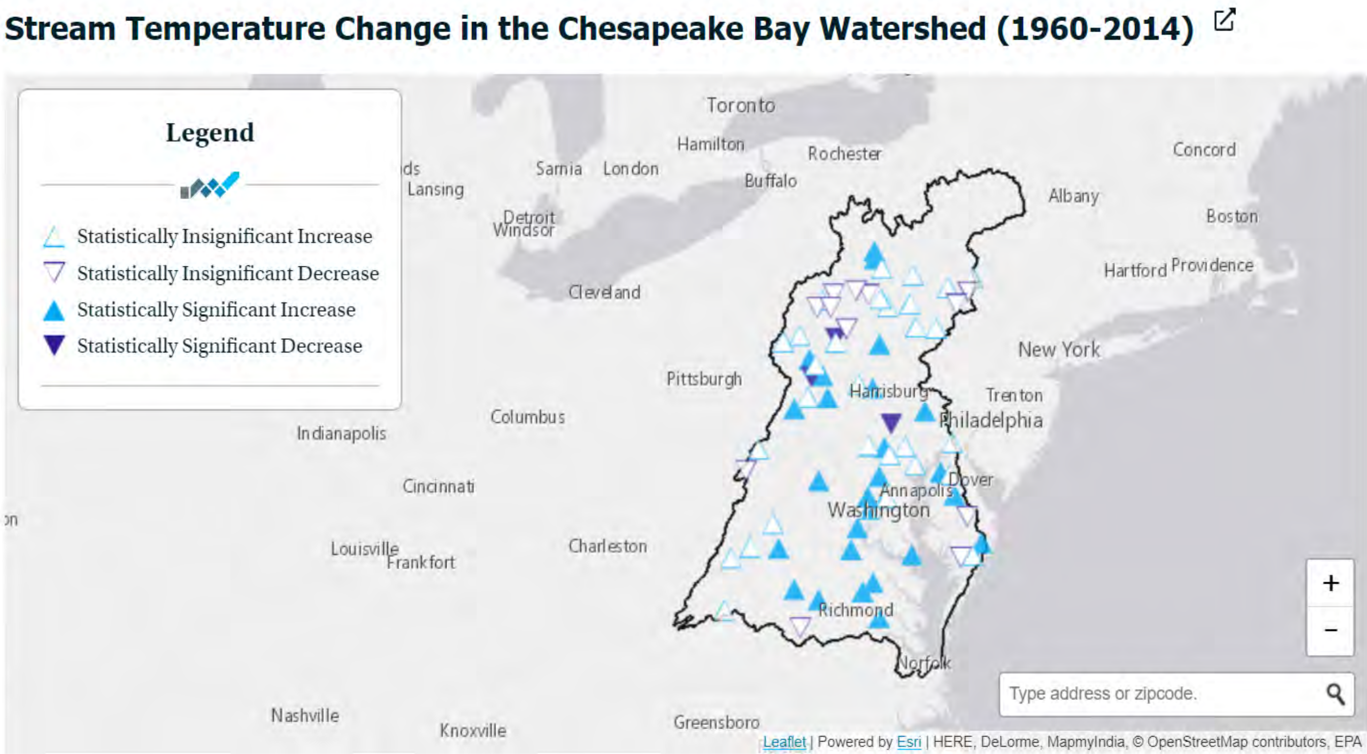


Figure IX-4. Climate change indicator showing the change in stream temperatures from 1960-2014 at USGS stream gauge stations in the Chesapeake Bay watershed. Chesapeake Progress, www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment.

OTHER INDICATOR AND TRENDS ANALYSIS PROGRAMS

In addition to the climate change indicators on Chesapeake Progress, there are other programs that have developed climate change indicators ranging from national (i.e., U.S. EPA Climate Change Indicator Program) and regionally specific (i.e., Chesapeake Bay Integrated Trends Analysis, NOAA CoastWatch) indicators assessing long-term changes in water temperature to water temperature indicators specifically designed around ecological impacts (e.g., Healthy Watersheds Assessment climate change indicator related to brook trout occurrence, forage indicators related to seasonal warming and habitat suitability). The following sections describe these efforts with the goal to provide examples of indicator strategies that could help inform methodologies and application options for the Tidal Bay Water Temperature Change Indicator(s).

U.S. EPA Climate Change Indicator Program

[*www.epa.gov/climate-indicators*](www.epa.gov/climate-indicators)
Program Point of Contact: Mike Kolian, U.S. EPA

The U.S. EPA Climate Change Indicator Program is a collaborative effort between EPA and 50 data contributors from government agencies, academic institutions, and other organizations to provide indicators reflecting climate change causes and effects. Summarized below are a subset of these indicators related to temperature. While these indicators focus on air temperatures, **the data and methods used for these indicators could provide insights on methodology approaches for the Tidal Bay Water Temperature Change Indicator**.

Global Air Surface Temperature

The EPA's U.S. and Global Temperature Indicator (Figure IX-5) synthesizes data from remote sensing, weather station surface measurements, and observations from buoys and ships on the ocean. It calculates annual temperature anomalies from 1901 to 2020 using the average temperature from a baseline period of 1901 to 2000. For example, an anomaly of 2.0 degrees means the average temperature was 2 degrees higher than the long-term average of the baseline. With the data as a time series, NOAA calculated monthly temperature means for each site and employed a homogenization algorithm to correct for error between the data types and regions. From there, averages were compounded and could be converted into monthly anomalies by comparing it to the long-term average.

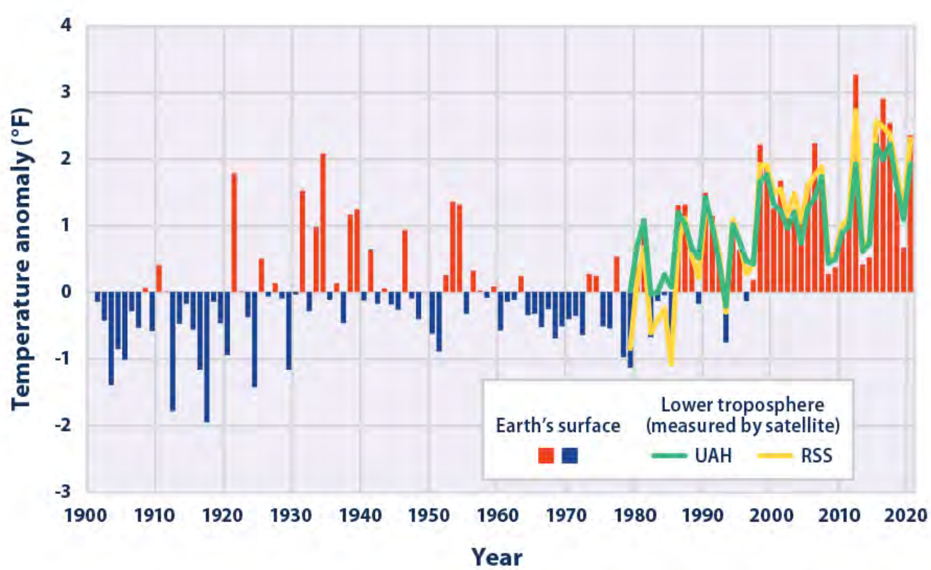


Figure IX-5. Temperature anomalies in the Contiguous 48 States, 1901–2020. U.S. EPA, www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-temperature

Seasonal Air Surface Temperature

The Seasonal Temperature Indicator (Figure IX-6) serves to reflect the fact that while average air temperatures increase throughout the year, increases may be larger in certain seasons. This indicator examines changes in average air temperatures in each season based on daily temperature measurements from more than 10,000 weather stations across the U.S. Similar to the U.S. and Global Temperature Indicator, it calculates annual temperature anomalies from 1896 to 2020 using the average temperature from a baseline period of 1901 to 2000. Daily temperature measurements at each site were used to calculate monthly anomalies, which were then averaged for each season to find temperature anomalies for each year. Regional anomalies were then averaged together in proportion to their area to develop state and national results.

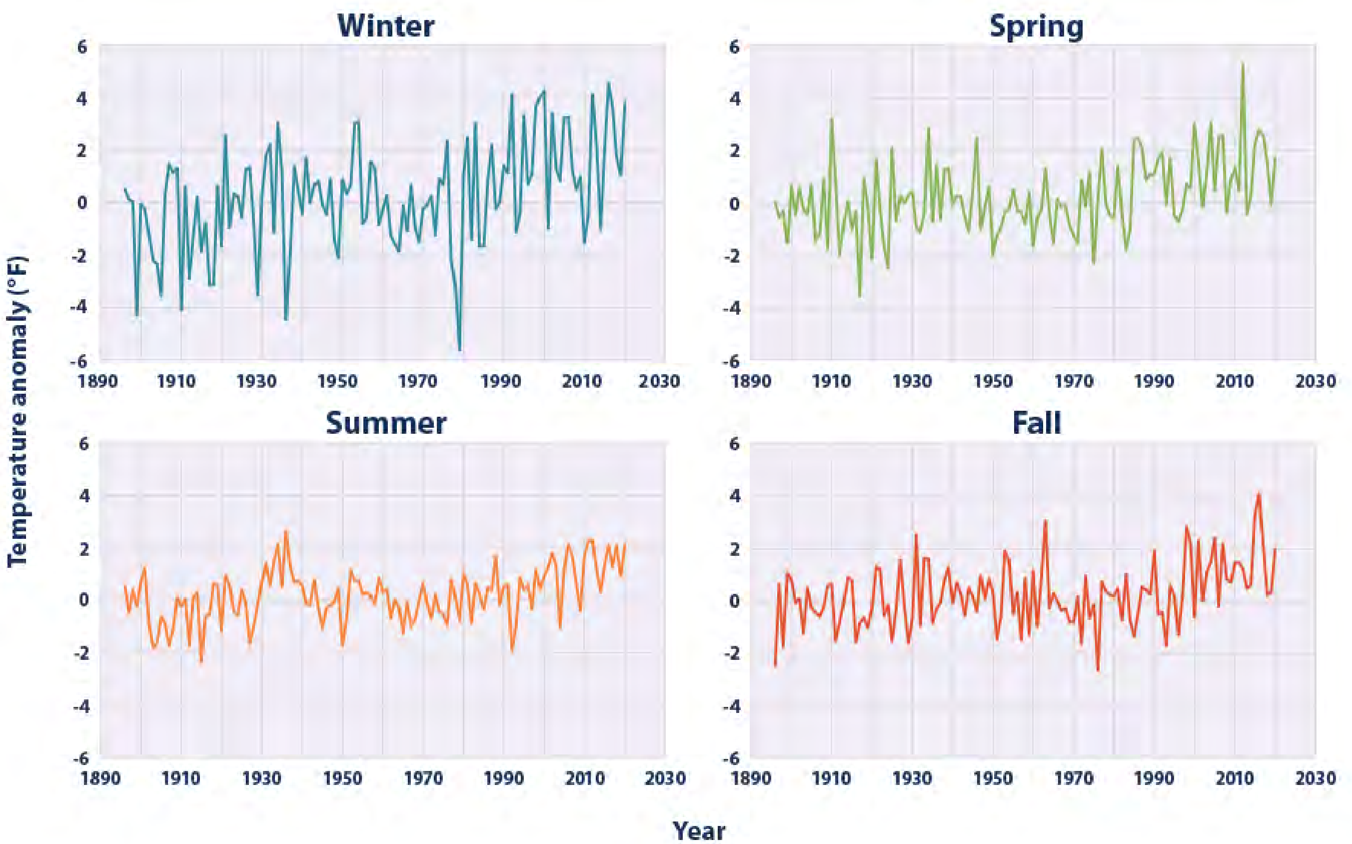


Figure IX-6. Average Seasonal Temperatures in the Contiguous 48 States, 1896–2020. U.S. EPA, www.epa.gov/climate-indicators/climate-change-indicators-seasonal-temperature

Heat Waves

The Heat Wave indicator examines trends over time in four characteristics of heat waves in the United States: frequency (number per year), duration (length in days), intensity (how hot it is), and season length (days between the first heat wave of the year and the last) (Figure IX-7). Weather data was analyzed from 1961 to 2019 for 50 large metropolitan areas, where the most people are vulnerable. They used hourly air temperature and humidity measurements to calculate apparent temperature, which is more relevant to human health. For consistency across the country, this indicator defines a heat wave as a period of two or more consecutive days where the daily minimum apparent temperature in a particular city is higher than the 85th percentile of historical July and August temperatures for that city. Given that criteria, they were able to identify heat waves and collect data on frequency, duration, intensity, and season.

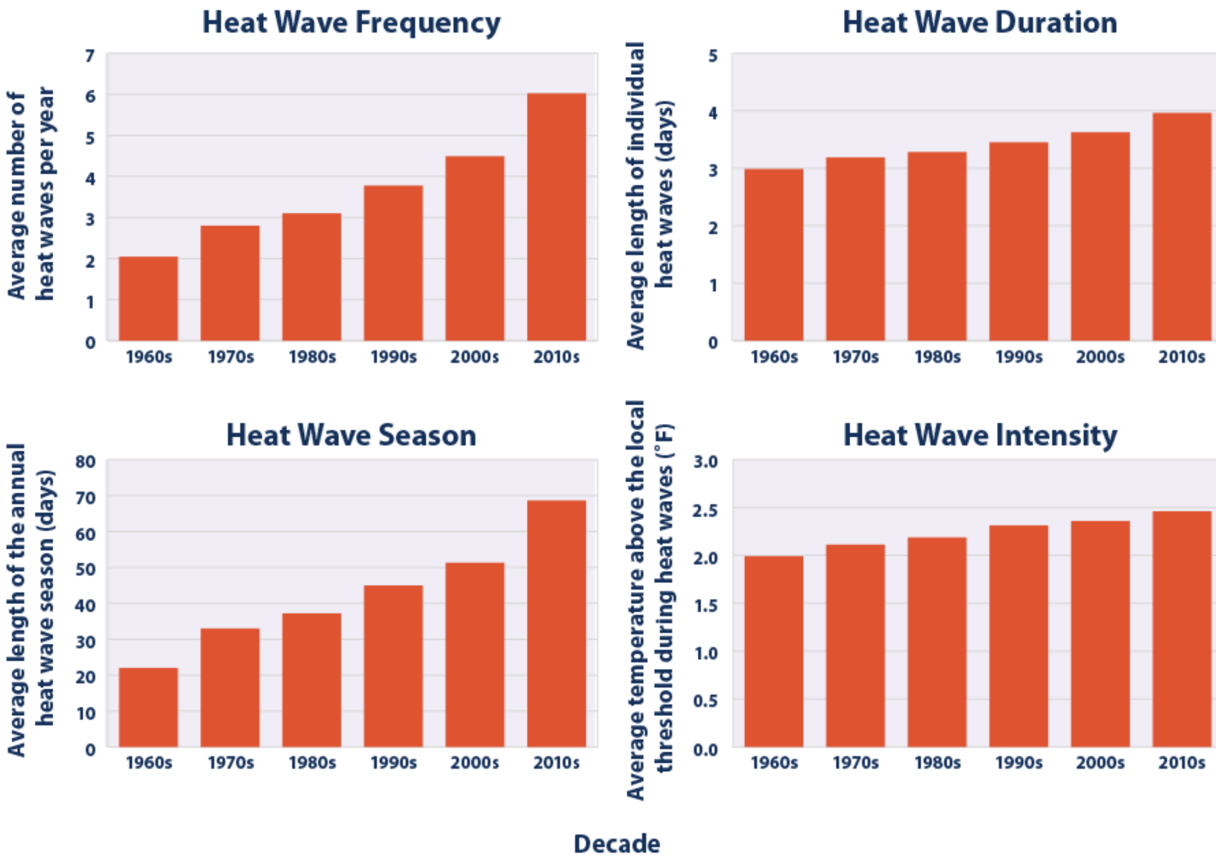


Figure IX-7. Heat Wave Characteristics in the United States by Decade, 1961–2019. U.S. EPA, [*www.epa.gov/climate-indicators/climate-change-indicators-heat-waves*](www.epa.gov/climate-indicators/climate-change-indicators-heat-waves)

Sea Surface Temperature

The Sea Surface Temperature indicator (Figure IX-8) tracks average global sea surface temperature from 1880 through 2020. While the early data was collected by inserting a thermometer into a water sample collected by lowering a bucket from a ship, today temperature measurements are collected more systematically from ships and buoys. NOAA reconstructed and filtered the data to correct for biases in the different collection techniques and to minimize the effects of sampling changes over various locations and times. It calculates annual temperature anomalies from 1880 to 2020 using the average temperature from a baseline period of 1971 to 2000. The data is averaged over 2-by-2-degree grid cells, with daily and monthly records averaged to find annual anomalies. A long-term trend was calculated for each grid cell using linear regression, where the slope of each grid cell's trend was multiplied by the number of years in the period to derive an estimate of total change.

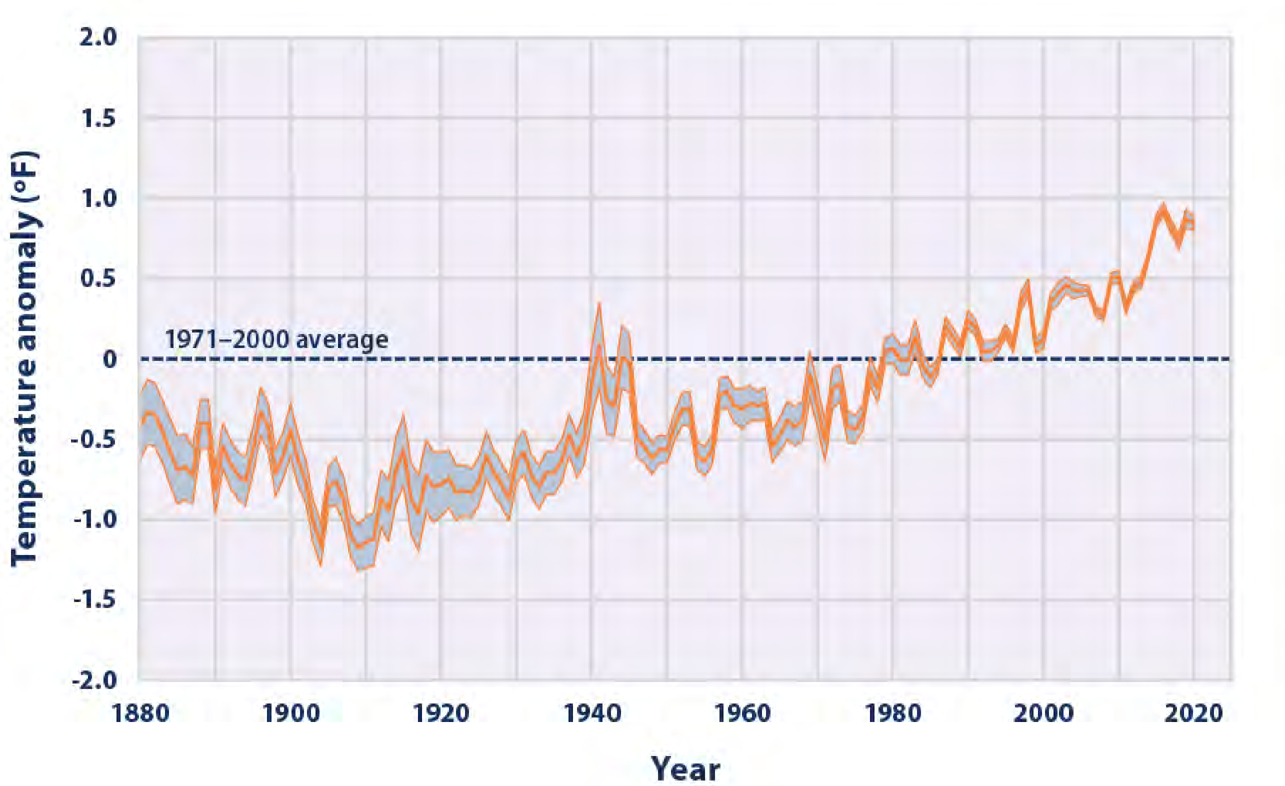


Figure IX-8. Average Global Sea Surface Temperature, 1880–2020. U.S. EPA, *www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature*

Chesapeake Bay Program Integrated Trends and Analysis Team

https://www.chesapeakebay.net/who/group/integrated_trends_analysis_team
Program Point of Contact: Rebecca Murphy, UMCES, and Jeni Keisman, USGS

The Integrated Trends Analysis Team (ITAT) aims to combine the efforts of the Chesapeake Bay Program analysts with those of investigators in governmental, academic, and non-profit organizations to identify collaborations that will enhance the understanding of spatial and temporal patterns in water quality. One of their annual partnership projects is to complete the Chesapeake Bay Tidal Trends Update. Maryland DNR, Virginia DEQ, DC and others have been sampling at 150+ stations since the 1980's 1-2 times per month for multiple parameters including water temperature (Figure IX-9). There is an extensive long-term coordinated tidal monitoring effort to analyze trends with this data. The data is collected and put into an R package called baytrends which has been designed to fit GAMs for the tidal Chesapeake Bay water quality data over time. A GAM is a statistical model in which a response of interest can be modeled as the sum of multiple smooth functions of explanatory variables (Murphy et al. 2019). These smooth functions can be constructed in many ways (Hastie and Tibshirani 1986, 1990), and GAMs allow for model shapes from linear to nonlinear – including patterns that change direction over time. The results from the different jurisdictions are submitted to the Chesapeake Bay Program and combined to show trends throughout the Bay through maps as demonstrated below.

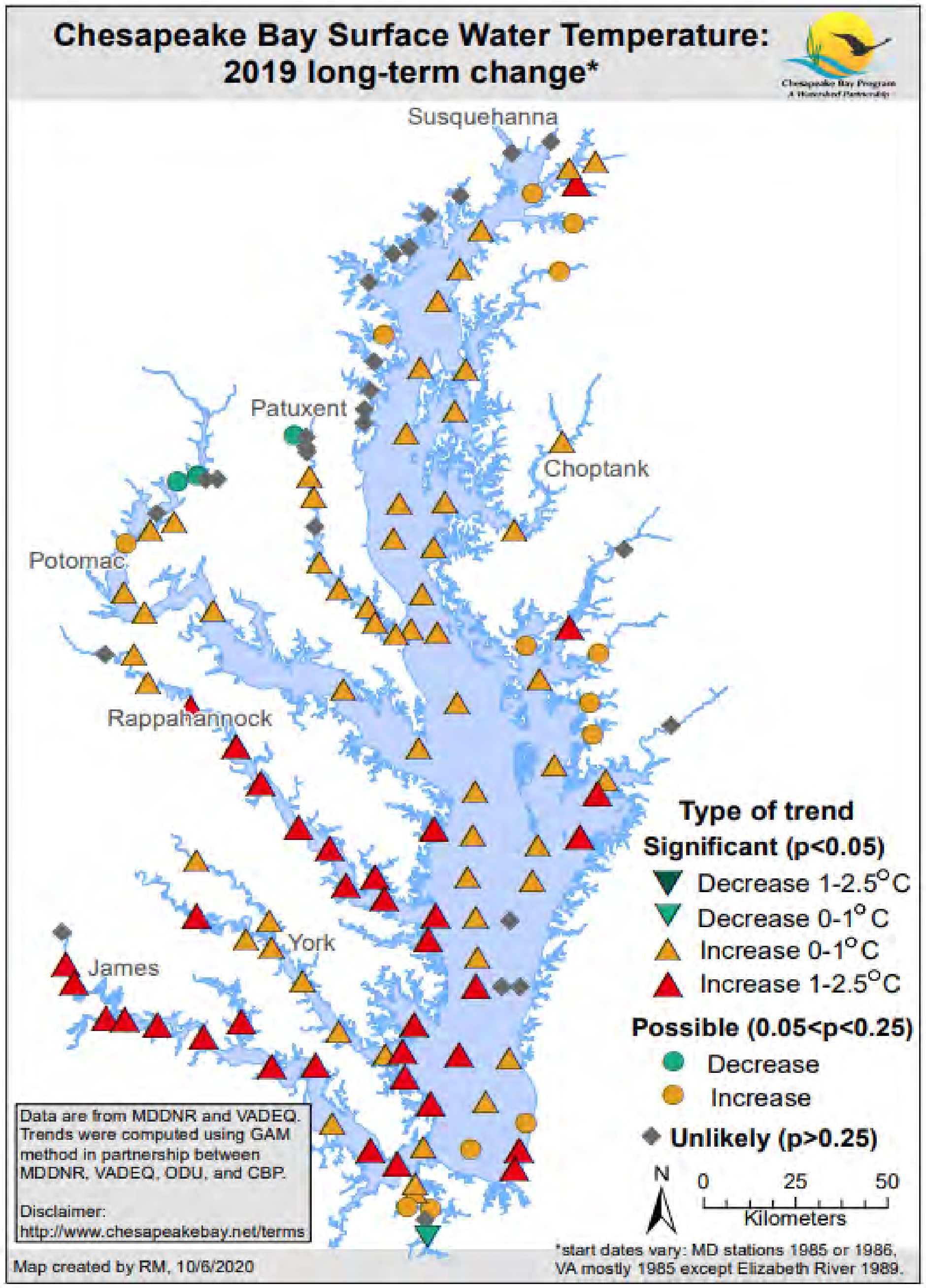


Figure IX-9. Long term flow-adjusted trends in bottom water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019 from the Integrated Trends Analysis Team (ITAT).

The annual tidal trend results represent multiple parameters, different depths (surface & bottom), different temporal dynamics (observed conditions & flow-adjusted), and various time periods and seasons (1985 - present, last 10 years, spring & summer CHLA). Significant contributors to this work include Jennifer Keisman (ITAT Lead), Renee Karrh (MDDNR), Mike Lane (ODU), and Rebecca Murphy (UMCES).

The ITAT physical change indicator for long-term Bay surface water temperature change and corresponding methodology using GAMS for trends analysis provides robust information that should be considered when developing options for the Tidal Bay Water Temperature Change Indicator related to ecological impacts. **While this indicator shows water temperature change on an annual temporal scale, the method could be used to develop seasonal trends or other**

identified time periods of interest where the data are available (Rebecca Murphy, UMCES, personal communication), which could be more suited for assessing impacts to fish or SAV.

U.S. EPA National Estuary Program Indicator Extended to Chesapeake Bay
https://eastcoast.coastwatch.noaa.gov/time_series_sst_gen.php?region=cd
Program Point of Contacts: Ron Vogel, NOAA
Contributors: M. Craghan, USEPA, and M. Tomlinson, NOAA

The U.S. EPA National Estuary Program partnered with NOAA CoastWatch to develop a website tool that utilizes remote sensing satellite data from various sources to produce graphs (Figure IX-10) and maps of monthly and annual averages and statistical trends from 2008-2018 of water temperature change along the East Coast. This project was extended to the Chesapeake Bay where the temporal and spatial averaging methodologies were based on recommendations in the STAC 2008 CBP Climate Report (Pike et al. 2008) (Figure IX-11).

Monthly average, all years
Seasonal difference in rate of change in the Chesapeake Bay

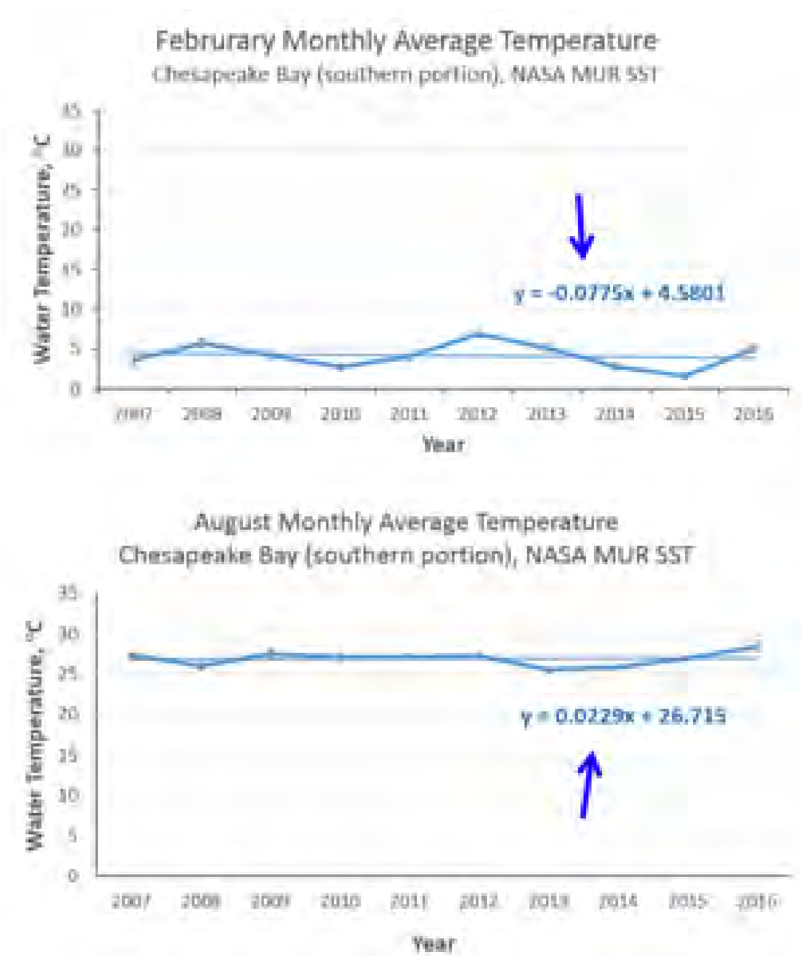


Figure IX-10. Example of graph outputs from the NOAA CoastWatch website demonstrating the seasonal differences in the rate of water temperature change from 2007-2016.

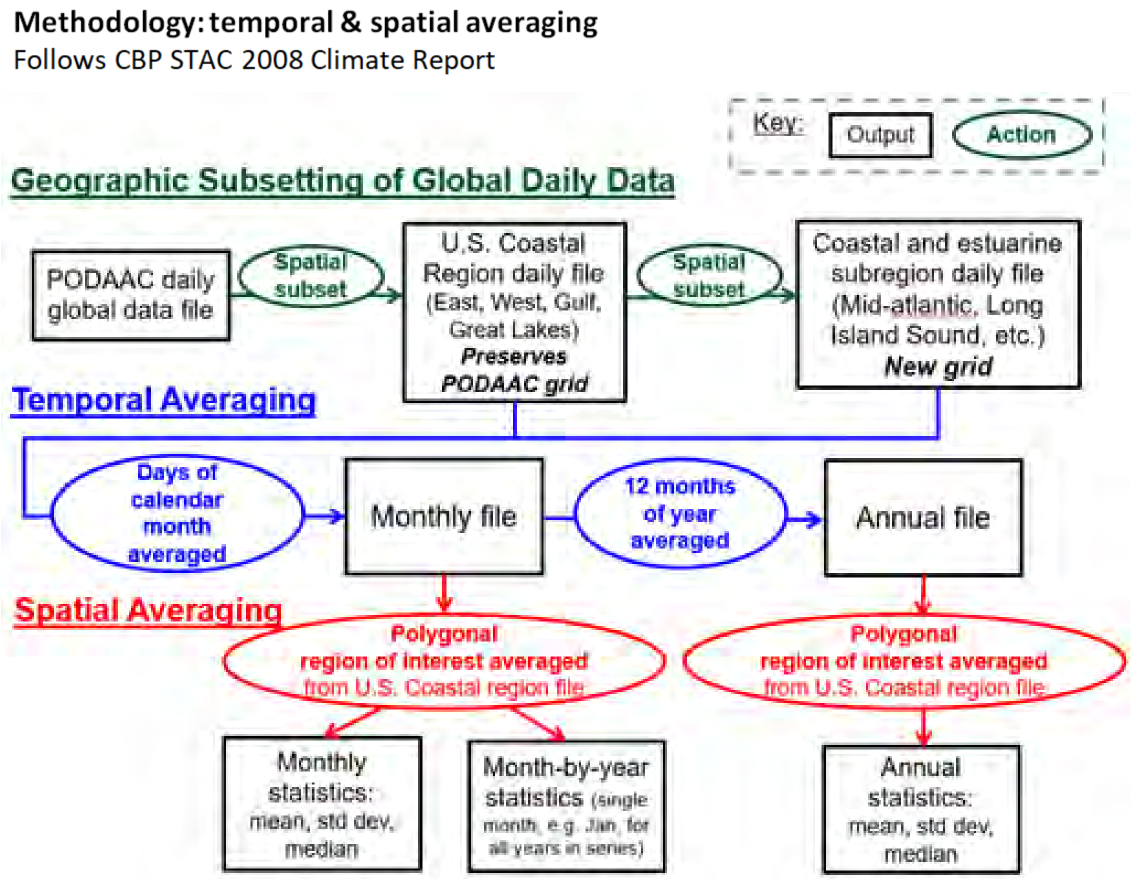


Figure IX-11. Flow chart demonstrating the temporal and spatial averaging methodologies for the NOAA CoastWatch water temperature change analyses based on recommendations found in the CBP STAC 2008 Climate Report (Pike et al. 2008).

The NOAA CoastWatch website is an interactive tool that allows users to select the monthly time period to run the trends analysis. **NOAA CoastWatch is an example of a customizable indicator that could be considered for the Tidal Bay Water Temperature Change indicator to allow the end user to select the time period of interest.**

Healthy Watersheds Assessment

The Healthy Watersheds Assessment (Roth et al. 2020) provides an example of how habitat conditions can be considered in assessing future probability of fish occurrence. Included in the assessment is the vulnerability metric, “Change in Brook Trout Probability of Occurrence with 6 degree Celsius Temperature Change” by catchment (Figure IX-12). This metric utilizes a model from Nature’s Network/USGS Conte Lab that predicts brook trout occurrence under present conditions and temperature increases from 2 to 6 degree Celsius scenarios. The 6-degree scenario provided the most sensitive signal of potential change across the Chesapeake Bay watershed regions. **Indicators developed with future scenarios in mind could support resilience planning by identifying areas to target conservation or restoration.**

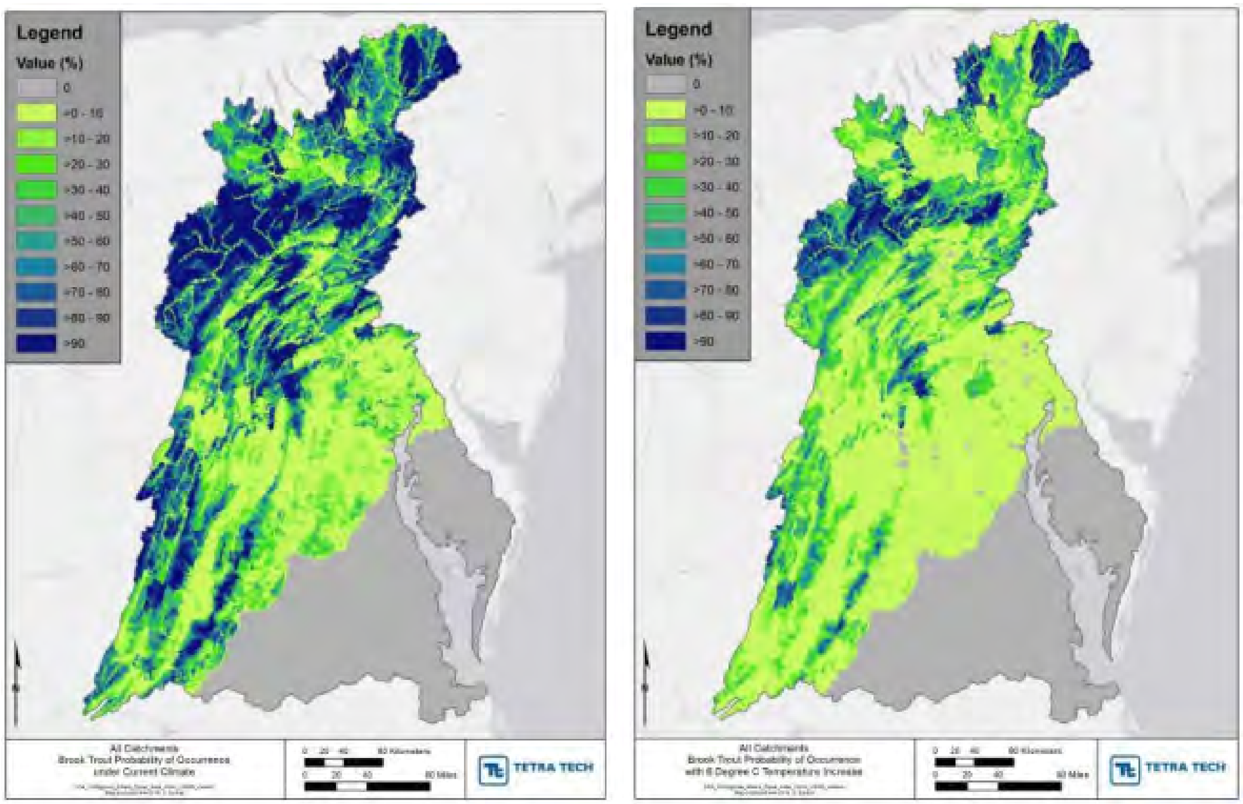


Figure IX-12. Probability of brook trout occurrence under current climate conditions (left) decreasing across much of the region with a 6 degree C increase in stream temperature (right). Source: Roth et al. 2020

Forage Indicator Development Efforts

The goal of the Forage Outcome stipulated in the 2014 Chesapeake Bay Watershed Agreement is to “continually improve the partnership’s capacity to understand the role of forage fish populations in the Chesapeake Bay...and to develop a strategy for assessing the forage fish base available as food for predatory species.” The Forage Action Team (FAT) is currently developing an initial suite of indicators to assess the forage base in the Bay. This indicator suite is expected to operate as an assessment tool for tracking the health of the Bay and to eventually inform management. In 2020, the FAT created the Forage Indicator Development Plan to lay out a framework for indicator development which follows a tiered approach. The Tier 2 indicators, which use the relationships between environmental factors and forage abundance to track forage status over time, may provide insight for the development of a Chesapeake Bay water temperature indicator. There are currently two Tier 2 indicators that may be of interest: the Springtime Warming indicator and the Habitat Suitability Index.

The Springtime Warming indicator will use a phenological temperature index to determine the timing of warming water temperatures in the Chesapeake Bay. Woodland et al. (2017) determined that the rate of springtime warming (i.e., how quickly water temperatures reached a threshold in spring) has a negative relationship with summer forage abundance. That is, the earlier in the year that water temperature warms up, the less forage are available as prey in the Bay. The indicator will consist of a time series of the integer day each year at which 500 degree-days (DD) was achieved using 5°C as a threshold and will provide insight into the effects of climate change on the forage base. Bay anchovy are a key forage species that exhibited a significant negative relationship with the rate of springtime warming and will therefore be the initial focus of this indicator. Other finfish (e.g., YOY weakfish) and invertebrates (e.g., polychaetes, crustaceans) that exhibited a relationship can be used to develop indicators in the future.

The Habitat Suitability Index will consist of a time series of area (or percent area of the Bay) available as suitable habitat for various forage species in the Chesapeake Bay. This indicator will be developed from the results of a habitat suitability modeling project that was wrapped up in 2020, which uses hydrodynamic models and water quality parameters (e.g., water temperature, salinity, dissolved oxygen) to assess the extent of suitable habitat for four key forage species: bay anchovy, juvenile spot, juvenile weakfish, and juvenile spotted hake. With these models, researchers were able to examine the annual and seasonal variations in abundance and distribution of the four forage species. The model results indicated that seasonal variability was more pronounced than annual variability, and there was a significant correlation between suitable habitat extent and forage abundance for bay anchovy in winter and juvenile spot in summer.

These forage indicators under development provide examples of how water temperature data can be directly applied to understand ecological impacts by using thresholds to identify suitable habitat.

DATA CONSIDERATIONS

When evaluating a Bay Water Temperature indicator, the 2018 climate change indicator implementation strategy (Eastern Research Group, Inc. 2018) recommended the use of two metrics, *in situ* measurements and satellite data, allowing for multiple lines of evidence to adequately represent changing water temperature in Chesapeake Bay. While a method has been developed for remote monitoring (a system of averaging grid squares), no method has been selected to aggregate *in situ* data. **Discussions on how best to compile the data from multiple sources and structure it into a formal indicator that aligns with desired management applications will be needed**. Tables IX-1 and IX-2 summarize available *in situ* and satellite data sources, respectively, and provides information on their temporal and spatial attributes.

Table IX-1. In-situ data sources for water temperature and initial assessment of strengths and weaknesses.

Data Source	***Type***	***Temporal extent***	***Temporal sampling interval***	***Spatial sampling interval***	***Underlying agency***	***Access***	***Strength***	***Weakness***
CB Monitoring Network (CBP)	ship	1985 - present	monthly, bimonthly	89 stations in main stem & tributaries	Bay-wide cooperative effort	https://datahub.chesapeakebay.net	long record, bay-wide	infrequent sampling interval
Eyes of the Bay Continuous Monitoring	Various anchored instruments	1985 - present (varies by station)	15 min	Multiple stations	Maryland Department of Natural Resources (various partners contribute)	http://eyesonthebay.dnr.maryland.gov/contmon/ContMon.cfm	continuous data in shallow environments, long record, high frequency sampling interval	data gaps
CBIBS (NOAA)	buoy	2008 - present	hourly	varies year to year the number of operational buoys	NOAA	https://buoybay.noaa.gov/	continuous hourly data	surface data only, limited spatial coverage, frequent temperature data gaps
CBL Pier (UMCES)	various pier attached instruments	1938 - present		single point	UMCES Chesapeake Biological Lab	https://cblmonitoring.umces.edu	exceptionally long record, high frequency sampling interval	single point
Thomas Pt. Lighthouse (NOAA)	C-MAN station	1985 - present	hourly	single point	NOAA National Data Buoy Center	https://www.ndbc.noaa.gov/station_history.php?station=tplm2	long record, high frequency sampling interval	single point

Table IX-2. Satellite data sources for water temperature and initial assessment of strengths and weaknesses.

Data Source	***Type***	***Temporal extent***	***Temporal sampling interval***	***Spatial sampling interval***	***Underlying agency***	***Access***	***Strength***	***Weakness***
Multi-satellite composite SST (NOAA)	satellite	2008 - present	daily	1 km	NOAA CoastWatch	https://eastcoast.coastwatch.noaa.gov	bay-wide, high spatial sampling interval, temperature values confirmed against CBIBS buoys at seasonal scale	spatial gaps in daily record, shorter record than other satellite data sets, will be phased out in future, older algorithm and older data corrections than other satellite data sets
Geo-Polar Blended SST (NOAA)	satellite	2002 - present	daily	5 km	NOAA Center for Satellite Applications & Research	https://coastwatch.noaa.gov	bay-wide, no spatial gaps in daily record	coarse spatial sampling interval for a satellite data set
Coral Reef Watch SST (NOAA)	satellite	1985 - present	daily	5 km	NOAA Coral Reef Watch	https://coralreefwatch.noaa.gov	bay-wide, no spatial gaps in daily record	combines two separate data sets for 1985-2002 and 2002-present intervals, coarse spatial sampling interval for a satellite data set
Multiscale Ultrahigh Resolution SST (NASA)	satellite	2002-present	daily	1 km	NASA JPL/ PODAAC	https://podaac.jpl.nasa.gov/	bay-wide, high spatial sampling interval, no spatial gaps in daily record	inaccuracy exists currently for 2002-2006 period, improved accuracy for full temporal extent expected in future version

Landsat Surface Temperature (USGS)	satellite	1982-present (Landsat 4,5,7,8)	every 16 days	100 m (thermal data)	USGS	https://www.usgs.gov/core-science-systems/nli/landsat/data-tools	bay-wide, highest spatial sampling interval	spatial gaps in daily record, infrequent sampling interval compared to other satellites, less accurate than other satellite data products (see note below)
Climate-Change Initiative SST (European Space Agency)	satellite	1981-2016	daily	5 km	European Space Agency Climate Change Initiative	https://climate.esa.int/en/projects/sea-surface-temperature/data	bay-wide, no spatial gaps in daily record	coarse spatial sampling interval for a satellite data set, temporal extent not expected to be extended on routine basis

Additional information and considerations on the above satellite data sets:

1) Selected data sets have spatial sampling interval 5 km or less; coarser data sets are not suitable for Chesapeake Bay
2) Selected data sets have institutional support
3) All the above data sets combine data from multiple instruments on multiple satellites
4) Satellite SST data generally has accuracy of 0.3 degree C or less; accuracy assessment per specific data set may not be available; Landsat surface temperature has accuracy of ~ 1.1 degree C for estuaries (Schaeffer et al. 2018)
5) All the above data sets have weaknesses in temporal extent, temporal sampling interval, spatial sampling interval, spatial gaps in daily record, or consistent accuracy across the temporal extent
6) NOAA has formulated plans for best-of-all-products SST data set to address the above weaknesses. The new data set will cover 1981-present with a daily temporal sampling interval, 2 km spatial sampling interval, no spatial gaps, and consistency in accuracy across the temporal extent (availability TBD)

Exploratory: Fish Habitat Applications for the Water Temperature Change Indicator

With the goal to connect the Tidal Bay Water Temperature Change Indicator with ecological impacts, the NOAA Chesapeake Bay Office through the NOAA-CRC Summer Internship Program has supported two internship projects to date exploring data application and conceptual ideas related to water temperature change and fish habitat considerations. These projects involved evaluating temporal and spatial data considerations related to fish spawning and developing conceptual ideas for connecting the water temperature data to fish habitat suitability. **These exploratory analyses can help inform conversations to identify management application options for the Tidal Bay Water Temperature Change Indicator.**

Multi-Data Source Evaluation Related to Designated Fish Habitat in Chesapeake Bay

Work by Shalom Fadullon, NOAA-CRC Intern, Breck Sullivan, CRC, and Julie Reichert-Nguyen, NOAA (2020)

Supported by the NOAA-CRC internship program, this project evaluated existing, long-term data sources to support the development of a Tidal Bay Water Temperature Change Indicator for the Chesapeake Bay tidal waters. The project assessed the feasibility of combining satellite and individual site data as recommended in the CBP climate change indicator strategy (Eastern Research Group, Inc. 2018) in relation to fish spawning habitat grounds.

We evaluated datasets from the CBP Long-Term Monitoring stations and the Multi-Satellite AVHRR. Early in the project it was discovered that the daily satellite data did not typically reach narrow areas upstream in the tributaries where there are designated fish spawning habitats (Figure IX-13). While there are CBP Long-Term Monitoring stations in these areas, they only include monthly samples. Daily data are needed to better connect a water temperature change indicator to fish spawning effects (Jim Uphoff and Stephanie Richards, Maryland Department of Natural Resources, personal communication).

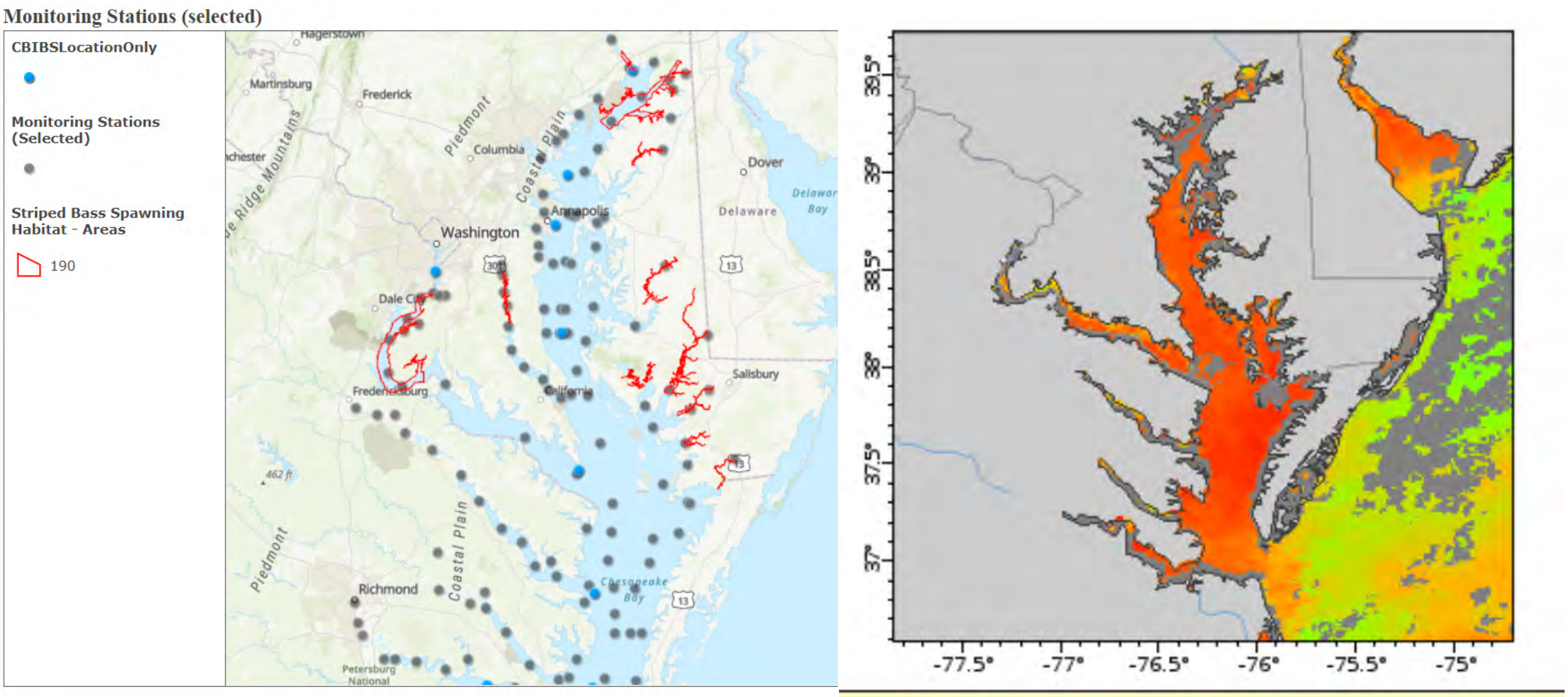


Figure IX-13. Location of designated fish spawning habitats (red), CBIBS buoys (blue), and CBP Long-Term Monitoring stations (grey) are shown in the map below (left).
Example of spatial coverage from Multi-Satellite AVHRR data (right).

There were a few locations where the two different data sources did overlap within a designated fish spawning habitat, including an area in the Potomac River (Segment POTOH1_MD; Figure IX-14).

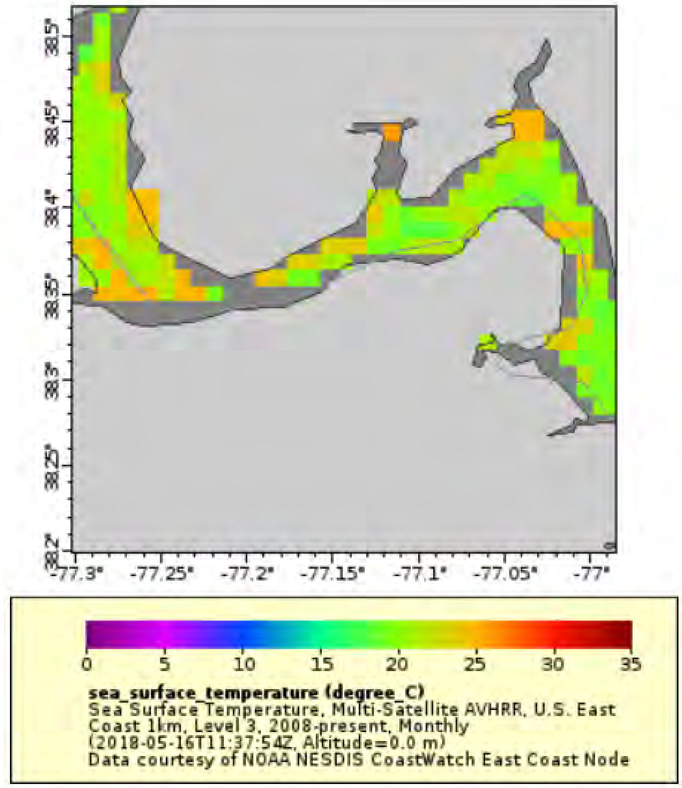


Figure IX-14. Long-term CBP Monitoring stations, RET2.1 and RET2.2, in the Potomac River segment POTOH1_MD (left) that align with Multi-Satellite AVHRR data (right).

Comparisons of the monthly averages from the long-term monitoring stations RET 2.1 with monthly averages from nearby daily Multi-Satellite AVHRR data from 2008-2019 were conducted to assess if the datasets produced similar results. Overall, the two datasets are comparable (Figure IX-15). Instances where the satellite or measured data are overestimating or underestimating the temperature should be further investigated.

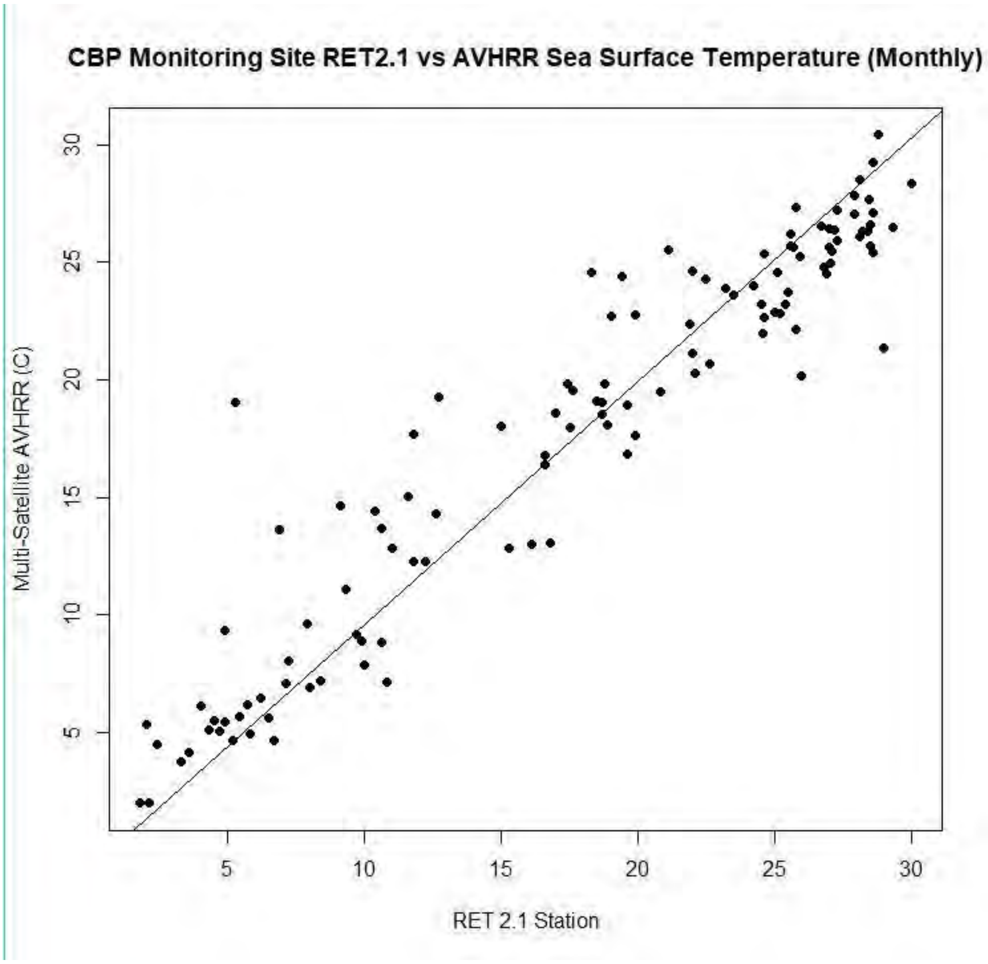


Figure IX-15. Comparison of CBP Monitoring Site RET2.1 data with Multi-Satellite AVHRR data from 2008-2019 in Potomac River segment POTOH1_MD.

A seasonal breakdown of the data could be explored to further assess the variability between the two datasets related to fish spawning cycles. Data gaps could be further evaluated to see if months with more cloud cover days demonstrate large differences from the measured values.

Depending on the management question being asked, there may be a data mismatch to fulfill all the spatial and temporal needs (e.g., preferred daily data unavailable in spawning location). Regarding satellite data, other sources should be explored beyond the Multi-Satellite AVHRR dataset, where daily data in the narrow tributaries may exist. **While there are data limitations in spawning areas, satellite and measured data are more abundant in the mainstem of the Bay and have shown to have a good fit. Combining these datasets to assess fish habitat requirements in the mainstem of the Bay related to latitudinal fish distribution could be feasible.**

Conceptual Ideas for the Tidal Bay Water Temperature Change Indicator Related to Fish Habitat

Work by Anissa Foster, NOAA-CRC Intern, Breck Sullivan, CRC, and Julie Reichert-Nguyen, NOAA, (2021)

Supported by the NOAA-CRC internship program, this project focused on compiling potential uses for a Tidal Bay Water Temperature Change Indicator related to fish impacts in Chesapeake Bay. **Concepts from the literature were reviewed to develop ideas for ecological impact indicators that connect water temperature change to fish habitat suitability. A persisting trend in the literature review is that climate-forced changes in species distributions are causing changes in both fishery operations and fisheries management (Link et al. 2015). Another is the increasing number of marine heatwaves.** Due to their severe negative impacts on coastal and ocean ecosystems, investigating resilience strategies with regards to these extreme events is crucial (Holbrook et al. 2020). Existing ecological metrics at NCBO provided insights into tools and concepts to build ecological indicators, such as temperature thresholds and seasonal change.

We developed two indicator concepts using information on striped bass habitat (Figure IX-16), but these concepts could be applied to other species of fish and even SAV where there are known habitat requirements. Spatially, to understand fish distribution change under a warming climate, water temperature data can be used to assess potential shifts in populations — particularly as the lower Bay warms faster than the upper Bay. For instance, striped bass prefer oxygenated, deeper areas, thriving in temperatures below 25°C (Thompson 2010). A water temperature change indicator that is structured related to fish habitat requirements could identify regions which serve as critical habitats to alleviate thermal stress during the summer months and ensure fish accessibility versus areas that are less optimal. Thompson (2010) outlines that striped bass require dissolved oxygen levels of at least 2 mg/L, thus a multi-metric approach (such as water temperature and dissolved oxygen) could allow for a more comprehensive assessment of available habitats.

The second concept was oriented towards striped bass survivorship. A heat wave indicator could track the characteristics of a heat wave related to fish habitat requirements to identify areas where fish may be exposed to more stressful habitat conditions affecting their survival. The indicator could examine trends in four key characteristics of heat waves (EPA 2021):

- Frequency: the number of heat waves that occur every year.
- Duration: the length of each individual heat wave, in days.
- Season length: the number of days between the first heat wave of the year and the last.
- Intensity: how hot it is during the heatwave.

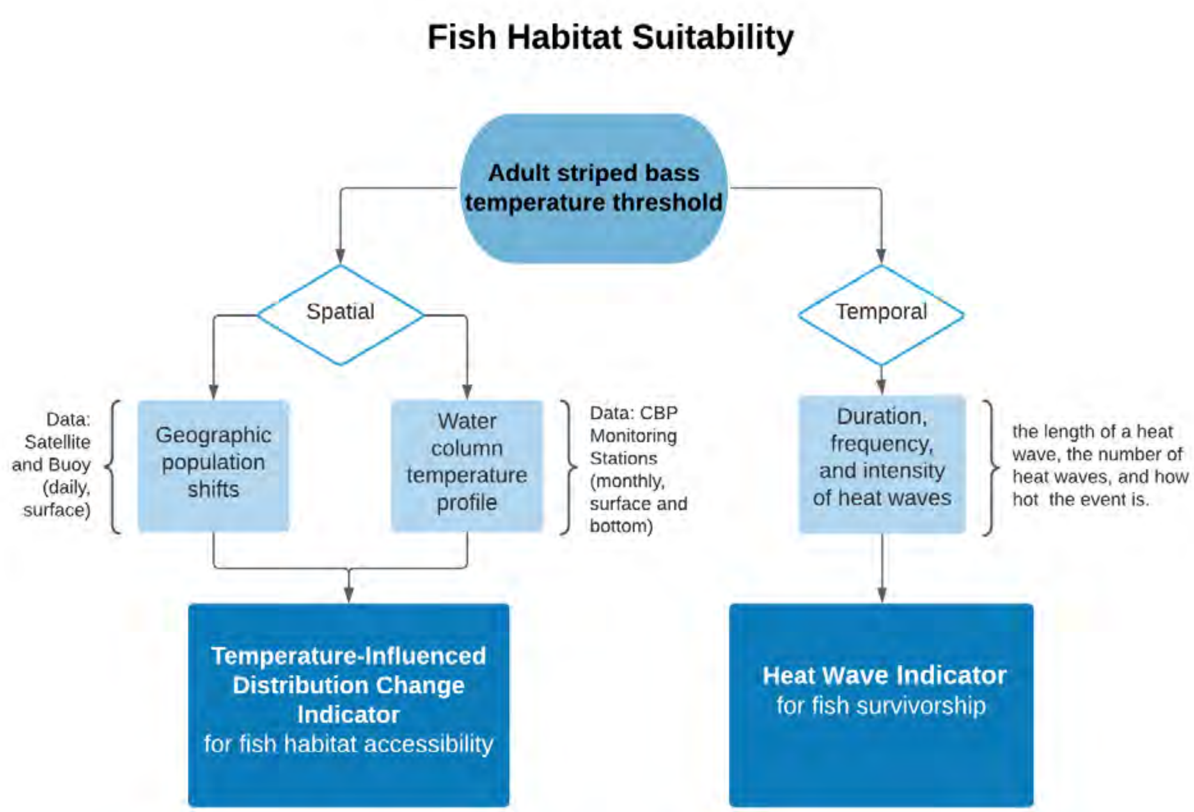


Figure IX-16. Conceptual ideas to connect Bay water temperature change with fish habitat suitability.

E. Evaluation

KEY FINDINGS

When just considering physical water temperature change in the Chesapeake Bay, indicators currently exist, including the ITAT water temperature trends analysis and the National Estuary Program's indicator extended to Chesapeake Bay using satellite data. However, to inform resilience management responses related to the water quality, habitat, and living resource goals, there is a need to connect the water temperature data to the ecological impacts at the appropriate temporal and spatial scales of the management question(s) being asked. Therefore, the indicator characteristics, methodologies and development depends on the specific management application that the indicator is needed to inform. Given that there could be multiple management questions around rising water temperatures, we may need more than one tidal Bay water temperature change indicator. Prioritizing the management needs will be important to identify which water temperature change indicators to pursue.

The review for the synthesis paper revealed that there is no one single data source that will meet all the desired criteria (temporal extent, temporal interval, spatial interval, accuracy, ongoing record, institutional support, etc.) to address management questions around habitats and living resources. Given the data limitations from individual data sources, a multi-data resource approach could allow for a more robust indicator by combining the advantages of different data sources: high temporal resolution from buoys and moorings; long-term data and bay-wide coverage from ships; bay-wide coverage with high spatial resolution from satellites (Table IX-3).

Table IX-3. Summary of advantages and limitations of different types of data sources (i.e., ship, buoy/mooring, satellite).

	SHIP	BUOY/MOORING	SATELLITE
Advantages	• bay-wide • vertical profile	• highest temporal sampling interval • surface-only or vertical profile	• bay-wide • highest spatial sampling interval • high temporal sampling interval
Limitations	• low temporal sampling interval • low spatial sampling interval	• lowest spatial sampling interval	• surface only

In reviewing the literature for potential uses of a Tidal Bay Water Temperature Change Indicator in connection with habitat and living resources, three common themes emerged: establishing habitat requirements, identifying critical thresholds, and evaluating the data from a seasonal standpoint. When considering fisheries management decisions, daily data are useful for decisions regarding spawning, while long-term monthly averages may be better suited for tracking adult distribution changes (Uphoff and Richards, Maryland Department of Natural Resources, personal communication). Indicators that incorporate future climate change scenarios could provide valuable information for resilience planning.

Figure IX-17 provides examples of management application options for a Tidal Bay Water Temperature Change Indicator depending on the management need. For instance, if the management need is to capture general long-term trends in changes to water quality, a coarser spatial (e.g., point data) and temporal (e.g., monthly) scale could be sufficient. However, if assessing changes to fish habitat to inform fisheries management decisions, a finer spatial (e.g., satellite) and temporal (e.g., daily) scale may be required.

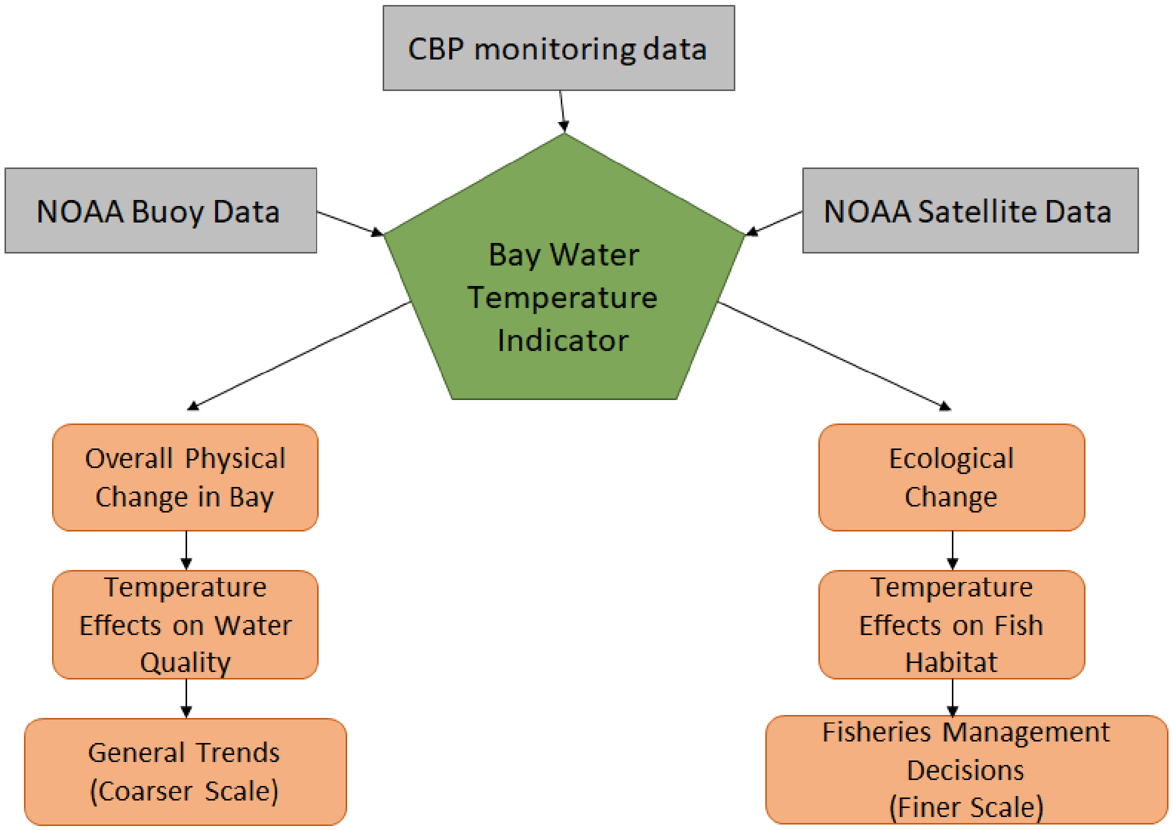


Figure IX-17. Flow chart demonstrating potential options for a Bay Water Temperature Indicator based on management applications.

The following are gaps in knowledge that need further assessment:

1) Better understanding of management needs to make decisions on resilience actions.
2) Scientific understanding to construct an indicator to meet the management need(s), i.e. development of a methodology, including selection of the specific data sources.
3) More linkages between environmental physical characteristics and biological suitability needs related to habitats and species of interest in relation to present and future conditions.

MANAGEMENT IMPLICATIONS

Given the time and effort to develop and maintain indicators, it will be important to get input from potential end users on the utility of any Tidal Bay Water Temperature Change Indicator before development. Doing this ahead of developing an indicator will better position the indicator to be useful in identifying and implementing strategies in managing affected resources from rising water temperatures in a strategic direction that optimizes resilience. Knowledge that is gained from the fish and SAV synthesis assignments should be considered when identifying options for the Tidal Bay Water Temperature Change Indicator. Additionally, information learned from the monitoring synthesis will be important to identify reliable data sources to support a Tidal Bay Water Temperature Change Indicator long-term.

A management criteria for any methodology for generating the indicator is flexibility to exchange the input data sets with new ones, as data sets lose funding, existing data sets' time series are reprocessed with new corrections applied, and new data sets with more desirable characteristics (accuracy, spatial resolution, temporal extent) become available. After replacement of the input data set(s), the indicator's entire time series will need to be recalculated. Infrastructure must be in place to accomplish this.

Overall, management considerations related to indicator longevity include:

- How and who will compile data from multiple sources in format that can be applied towards indicator development for the temporal and spatial management scales of interest?
- How and who will maintain and update the indicators after they have been developed?
- Does the indicator methodology allow flexibility if there is a change in data availability?

FURTHER FOLLOW-UP SYNTHESIS WORK PLANNED OR UNDER CONSIDERATION

- More synthesis of existing indicator methodologies
    - GAM trends analyses (R. Murphy et al., 2019)
    - Multimetric indicator (Q. Zhang et al., 2018)
- Incorporating climate change projection information from the CBP Modeling Workgroup and other sources. Range of future protections could be compared to present trends to inform management responses under a resilience lens.
- Consideration of indicators that include multiple stressors (e.g., temperature, dissolved oxygen, salinity, water flow) when making connections to ecological impacts. A multi-metric strategy that considers multiple of a species' habitat requirements (including water temperature thresholds) could allow for a more comprehensive

assessment of available habitats. However, the complexity of the indicator usually increases as more parameters are incorporated. Therefore, it will be important to gauge available resources to allow the inclusion of multiple metrics.
- Incorporate discussion on successor species - new species that are moving into Chesapeake Bay with the habitat changes (e.g., brown shrimp, cobia, red drum).
- Connect the Tidal Bay Water Temperature Change Indicator to societal impacts - CRWG looking to coordinate with Stewardship GIT.
- Consider the role of nature-based practices in reducing global air temperatures, which would ultimately benefit the mainstem of the Bay in the long-term. A recent modeling study in Nature (Girardin et al. 2021) demonstrated that nature-based solutions, such as forests and wetlands, contribute to lowering global temperatures in the long term. They emphasized that nature-based solutions must be designed for longevity, particularly developing strategies that protect long-term carbon-sink potential.

F. Bibliography

REFERENCES CITED

Blake A. Schaeffer, John Iiames, John Dwyer, Erin Urquhart, Wilson Salls, Jennifer Rover & Bridget Seegers (2018) An initial validation of Landsat 5 and 7 derived surface water temperature for U.S. lakes, reservoirs, and estuaries, International Journal of Remote Sensing 39:22, 7789-7805, DOI: 10.1080/01431161.2018.1471545

Environmental Protection Agency. (2021). Climate Change Indicators: Heat Waves. EPA.gov. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves

Girardin, C., Jenkins, S., Seddon, N., Allen, M., Lewis, S.L., Wheeler, C.E., Griscom, B.W., Malhi, Y. 2021. Nature-based solutions can help cool the planet - if we act now. Nature. www.nature.com/articles/d41586-021-01241-2

Haiyong Ding and Andrew J. Elmore (2015) Spatio-temporal patterns in water surface temperature from Landsat time series data in the Chesapeake Bay, U.S.A., Remote Sensing of Environment 168, 335–348, http://dx.doi.org/10.1016/j.rse.2015.07.009

Roth, N., Wharton, C., Pickard, B., Sarkar, S., and Lincoln, A.R. 2020. Chesapeake Healthy Watersheds Assessment: Assessing the Health and Vulnerability of Healthy Watersheds within the Chesapeake Bay Watershed. Report prepared by TetraTech to the Chesapeake Bay Program, May 20, 2020.

Holbrook et al. 2020. Keeping pace with marine heatwaves. Nature Reviews Earth & Environment.
https://www.researchgate.net/profile/Neil-Holbrook-2/publication/343261891_Keeping_pace_with_marine_heatwaves/links/5f26623c458515b729fb45c2/Keeping-pace-with-marine-heatwaves.pdf

Jason S. Link, Roger Griffis, Shallin Busch (Editors). 2015. NOAA Fisheries Climate Science Strategy. U.S. Dept. of Commerce, NOAA Technical Memorandum NMFS-F/SPO-155, 70p
https://spo.nmfs.noaa.gov/sites/default/files/TM155.pdf

Rebecca R. Murphy, Elgin Perry, Jon Harcum, Jennifer Keisman (2019) A Generalized Additive Model approach to evaluating water quality: Chesapeake Bay case study, Environmental Modelling & Software 118, 1-13, https://doi.org/10.1016/j.envsoft.2019.03.02

Thompson, J. S., Rice, J. A., & Waters, D. S. (2010). Striped bass habitat selection rules in reservoirs without suitable summer habitat offer insight into consequences for growth. Transactions of the American Fisheries Society, 139(5), 1450-1464.
https://www.researchgate.net/publication/233233127_Striped_Bass_Habitat_Selection_Rules_in_Reservoirs_without_Suitable_Summer_Habitat_Offer_Insight_into_Consequences_for_Growth

Pyke, C. R., R. G. Najjar, M. B. Adams, D. Breitburg, M. Kemp, C. Hershner, R. Howarth, M. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, and R. Wood. 2008. Climate Change and the Chesapeake Bay: State-of-the-Science Review and Recommendations. A Report from the Chesapeake Bay Program Science and Technical Advisory Committee (STAC), Annapolis, MD. 59 pp.

Qian Zhang, Rebecca R. Murphy, Richard Tian, Melinda K. Forsyth, Emily M. Trentacoste, Jennifer Keisman, Peter J. Tango (2018) Chesapeake Bay's water quality condition has been recovering: Insights from a multimetric indicator assessment of thirty years of tidal monitoring data, Science of the Total Environment 637–638, 1617–1625, https://doi.org/10.1016/j.scitotenv.2018.05.025

ADDITIONAL RESOURCES

The recently NOAA-funded projects[7] incorporating climate change components related to fish distribution and abundance trends and indicators of habitat quality could offer valuable information in connecting the Tidal Bay Water Temperature Change Indicator to ecological impacts and provide insights on potential management responses. The principal investigators from these projects could be invited to the STAC workshops given their expertise in evaluating ecological effects from changing climate conditions. Summaries of their projects are described below:

Virginia Polytechnic Institute & State University (Virginia Tech) project titled, "Striped bass and summer flounder abundance trends and influencing factors in the Chesapeake Bay: an ecosystem-based evaluation" will:

- quantitatively assess the environmental, habitat variability and fishing intensity impacts on summer flounder and striped bass species abundance, distribution, and productivity in the Chesapeake Bay;
- assess fish community structure changes at long-term, interannual time scales and investigate trait and life history patterns that have similar or contrary trends with summer flounder and striped bass to better understand the mechanisms of their changes;
- detect or validate the potential climate change caused changes in habitat parameters for summer flounder and striped bass abundance and distribution in the Bay, and in fish community;
- investigate the environmental factor(s) and climate indices that can guide management caused by climate change.

This project aims to develop models to provide fishing communities and fishery managers with tools to better predict the key species of interest and viable fish communities during changing climate and habitat conditions. This project would addresses research priority #1 - synthesis and analysis of existing information that connects living resource responses to changing habitat, climate and other environmental conditions.

University of New Hampshire (UNH) project titled, "Leveraging multi-species and multi-year telemetry datasets to identify seasonal, ontogenetic, and interannual shifts in habitat use and phenology of Chesapeake Bay fishes" will analyze a variety of telemetry datasets for striped bass, river herring, cownose rays, dusky sharks, and horseshoe crabs, collected by the Smithsonian Environmental Research Center over the past ten years to identify species specific thermal and other indicators of habitat quality. The project plans to integrate telemetry data with habitat characteristics to develop species, season, and size based habitat distribution

---

[7] Past and Current Chesapeake Bay Fisheries Science Funded Research: https://www.fisheries.noaa.gov/past-and-current-chesapeake-bay-fisheries-science-funded-research

models in order to identify important indicators of habitat quality and use by fish in the Chesapeake Bay. This project addresses research priority #1 - synthesis and analysis of existing information that connects living resource responses to changing habitat, climate and other environmental conditions.

Another additional resource includes the Mid-Atlantic Fishery Management Council and partners' East Coast Climate Change Scenario Planning Initiative.[8] This effort includes fishery scientists and managers working collaboratively on identifying jurisdictional and governance issues revolving around climate change and effects to fisheries, such as shifting stocks.

---

[8] East Coast Climate Change Scenario Planning Initiative: https://www.mafmc.org/climate-change-scenario-planning

Appendix M
Synthesis Element 10 (Revised): Needs for Enhancing Monitoring Networks for Watershed Water Temperature Change Impacts

Synthesis Element 10 (Revised): Needs for Enhancing Monitoring Networks for Watershed Water Temperature Change Impacts

Abstract:

- There is extensive temperature monitoring, carried out by multiple agencies, that supports local to baywide tracking of water temperature both spatially and over time.
- There are data gaps for monitoring of temperature thresholds important to living resources. These gaps include high temporal frequency data at the reach-scale in the watershed and for nearshore, shallow tidal waters in the bay. There is interest in coincident air temperature monitoring.
- Results from a poll in the first 2021-22 Rising Water Temperature STAC Workshop event in this series that indicated our Chesapeake Bay community is most interested in improving our understanding for responses of impacted resources (e.g., hypoxia, fish distributions, bird distributions, wetland migration) as a function of temperature change. Less interest was expressed in more temperature monitoring.

A. Contributors

Peter Tango U.S. Geological Survey (USGS), Breck Sullivan, U.S. Geological Survey, and John Clune U.S. Geological Survey, and Amy Goldfischer, Chesapeake Research Consortium (CRC).

B. Resources

Nontidal water quality data resources referenced in this appendix are from the Chesapeake Bay Program's nontidal network.

Primary resources for the tidal monitoring datasets include outputs of the 2017-18 Goal Implementation Team (GIT) funded project on climate indicators for the Chesapeake Bay Program conducted for the Climate Resiliency Workgroup. Two documents located on the CBP (2022) Climate Resiliency Workgroup webpage (Climate Resiliency Workgroup | Chesapeake Bay Program) under *Projects and Resources – Climate Change Indicator Frameworks* contain the key reference material:

- CBP (2017) Excel spreadsheet: Monitoring networks 9-21-17.

- See item #10, "Bay Water Temperature" in CBP (2018) Climate Change Indicators for the Chesapeake Bay Program: An Implementation Strategy. Submitted to: Chesapeake Bay Program 410 Severn Avenue, Suite 109 Annapolis, MD 21403. Submitted by: Eastern Research Group, Inc. 2300 Wilson Blvd, Suite 350 Arlington, VA 22201. Revised Edition July 13, 2018

Additional insights are provided from published papers, Chesapeake Bay Program (CBP) webpages, and the Water Quality Standards Attainment and Monitoring Outcome Narrative Analysis completed by the Monitoring Team at the Chesapeake Bay Program during activities linked to work for the CBP Strategic Review System (SRS).

C. Approach

The approach to summarize bay and watershed temperature measurement resources was to reference the following:

a. 2017-18 GIT-funded research synthesis materials prepared for the CBP Climate Resiliency Workgroup during the evaluation of available data sources to support the development of a Bay Temperature Indicator,
b. The newest reference to Community Science monitoring in the bay and watershed where community science-based data are reported to the Chesapeake Monitoring Cooperative and are collated and made publicly available through their online Chesapeake Data Explorer database, and
c. Historical time series developed from Chesapeake Bay Program's nontidal network monitoring program.

D. Synthesis

<u>Overview of Watershed and Tidal Bay Temperature Data</u>

Diverse data resources exist on water temperature measurements in the watershed and bay. Primary resources are characterized as having well represented spatial distribution with consistent data collection methods for extended time series**.** Secondary resources are more limited in their spatial distributions, measurement frequencies, or duration of consistent data collection over time. Multiple datasets have been used in the analysis and reporting of temperature trends (e.g., Annual Trends by CBP Integrated Trends Analysis Team). Trend results have been presented with different spatial resolution, spatial coverage and time series from long-term single site records to regional multi-site network expressions of temperature change. The importance of any particular dataset for indicator development and analysis will depend on the utility of the indicator to support decision making on management actions and policy decisions, and whether or not any of the existing datasets provide the type of data to inform such an indicator. An example of a management relevant indicator based on local to regional water temperature records may include a Spring Warming Indicator (for fisheries management interests). It is notable that other management relevant indicators developed from local to regional temperature data include Frost Free Days (an agriculturally relevant indicator affecting growing seasons, planting and harvest times, crop options, water use, etc.) and Tropical Nights/Cooling Degree Days (an issue that affects living resource distributions, human health, socioeconomic well-being related to energy needs and energy use, etc.). These indicators are air temperature related and, while important for many managers, are not derived from our water temperature datasets.

Watershed

Chesapeake Bay Program Nontidal Monitoring Network

The current nontidal monitoring network has 123 water-quality monitoring stations (Figure 1). The network was established in September 2004 with the signing of a Memorandum of Understanding (MOU) where the seven jurisdictions, the Susquehanna River Basin Commission, and USGS all use the same set of standardized CBP protocols that are based on USGS field sampling methods and EPA-approved analytical lab methods. Water temperature data collected at the sites previously supported development of the watershed temperature indicator. These data will be compiled in an upcoming USGS data release described in a later section.

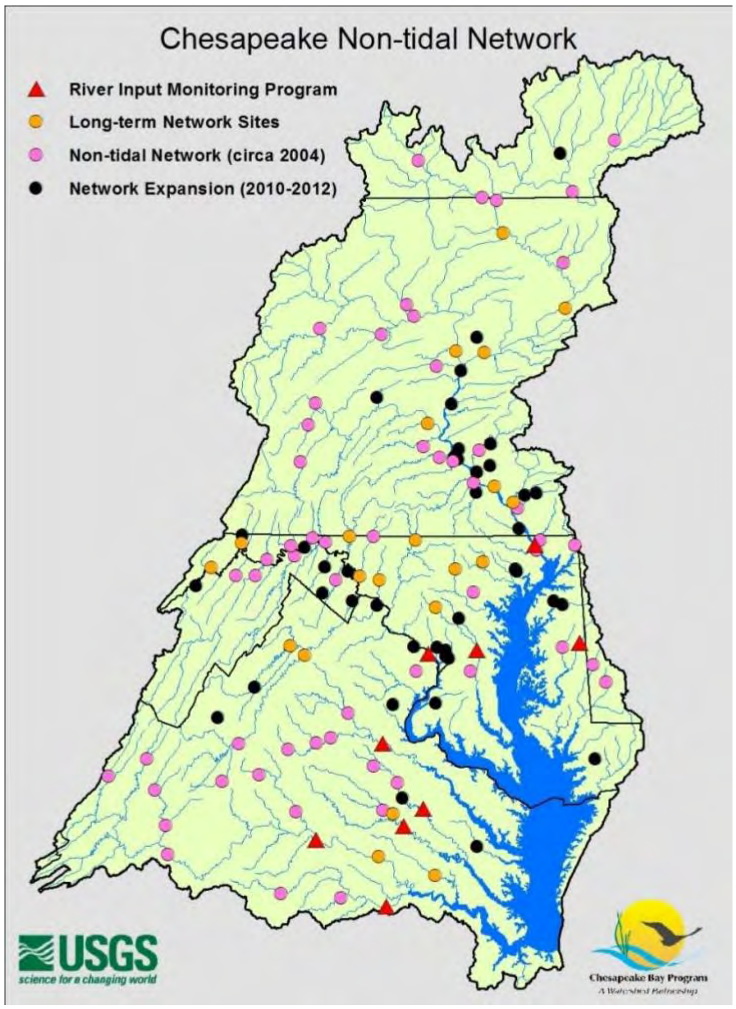


Figure 1. Chesapeake Bay Nontidal Network.

Dataset: Sub-annual stream water temperatures.
Source description: Directly sampled stream water temperatures at designated stream gage sites.
Organization that collects the data: USGS.
Data source contact: John Jastram, USGS, jdjastra@usgs.gov.
Rationale for selection: Based on the NWIS dataset of stream gages, which is the best available collection of physical stream parameters: This quality-controlled dataset further enhances the data by limiting potential issues with confounding factors or sites with limited data availability.
Temporal coverage: 1960–present* (*data review for the indicator was current through 2016).
Frequency: Sub-annual, but data are presented as trend over period of record.
Spatial coverage: Chesapeake Bay watershed and immediate surrounding area (129 stations total; 72 in the Chesapeake Bay watershed).
Spatial scale/resolution: Data for individual stations.
Access to data https://waterdata.usgs.gov/nwis.

Watershed Datasets

Additional nontidal datasets

Discrete and continuous water quality monitoring program water temperature datasets are being summarized from the National Water Information System, Water Quality Portal and Chesapeake Monitoring Cooperative data bases are being synthesized by g USGS (J.W. Clune, USGS, oral commun., 2023). Datasets of the Susquehanna River Basin Commission, Pennsylvania Department of Environmental Protection, Interstate Commission on the Potomac River Basin are known, may not be housed in the Water Quality Portal and represent additional opportunities to expand the temperature data resources available for synthesis and analysis (J. W. Clune, USGS, oral commun., 2023).

Tidal Bay

Primary data sources reflect broad tidal bay coverage, well represented spatial distribution with extended time series**.** The two primary datasets recognized in this review are the Chesapeake Bay Long-term Water Quality Monitoring Program and the National Oceanic and Atmospheric Administration (NOAA) NESDIS Satellite-based data. Secondary data resources reflect high quality data that, by comparison to the primary datasets, are more constrained in some manner (e.g., of limited density, spatial distribution and/or temporal coverage). Nine secondary datasets are further recognized resources. Dataset details are provided here:

Tidal Bay: Primary datasets

Chesapeake Bay Long-term Water Quality Monitoring Program

The current tidal water quality monitoring network was established in 1984, but its first full year of data collection was in 1985. There are 154 active stations sampled for physical, chemical, and biological parameters throughout the water column with baywide consistent collection and analysis protocols (Figure 2). One or more monitoring sites are located in each of the 92 tidal Bay segments. Stations are sampled 1 or 2 times per month depending on location and season for a total of 15 to 16 cruises that collect vertical profiles of water quality conditions.

Monitoring results are used to assess water quality standards attainment and evaluate the effectiveness of management actions through status and trends assessments for habitat conditions across space and through time. This program is supported under the federal Clean Water Act 117e program which includes 1:1 matching support from jurisdictional grant partners.

Data are available through the Chesapeake Bay Program DataHub. The DataHub is the Chesapeake Bay Program's primary tool for searching and downloading environmental data for the Chesapeake Bay watershed. This interface provides access to several types of data related to the Chesapeake Bay. Chesapeake Bay Program databases can be queried based upon user-defined inputs such as geographic region and date range. Each query results in a downloadable, tab- or comma-delimited text file that can be imported to any program (e.g., SAS, Excel, Access) for further analysis.

To ensure data accuracy, the Chesapeake Bay Program maintains a Quality Assurance Program that monitors and tracks several environmental datasets that look at pollutants, water quality, land use, algae, fish, crabs and submerged aquatic vegetation.

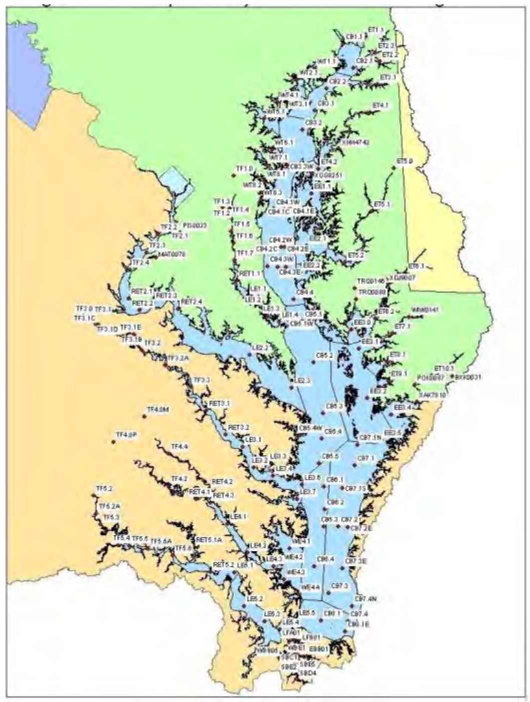


Figure 2. Tidal Chesapeake Bay Long-term Water Quality Monitoring Network. Source: CBP.

Source description: Annual measurement program, water temperature measurements obtained by hand-held sensor lowered into the water transiting the water column, all mainstem salinity zones, and many tidal tributaries up to the head of tide.

Source agency: U.S. EPA Chesapeake Bay Program Office
Source access: CBP 2023. Data Hub
DataHub(chesapeakebay.net)
Source contact: Mike Mallonee, ICPRB@CBPO, Data Manager mmallone@chesapeakebay.net ,
Peter Tango, USGS@CBPO Chesapeake Bay Monitoring Coordinator
ptango@chesapeakebay.net
Temporal Coverage: mid 1984-present
Frequency: Data collected 2x per month June to September and targeting 1x per month the remainder of the year. Non-summer months sampling frequency has varied over time.
Spatial scale/resolution: Point samples throughout the mainstem bay and the 9 major tidal tributaries and many smaller tidal sub-estuaries
Layers: Surface (Open Water Designated Use), Middle (Deep Water Designated Use) and Bottom (Deep Channel Designated Use).
Applications: Status, Trends, Model development/calibration/verification, water quality standards attainment assessment, policy making, communication, research, outreach

NOAA Satellite Data:

This is an ongoing NOAA project to develop a remotely sensed estuarine surface water temperature product. This product consists of daily surface water temperature measurements obtained by satellite-based sensors, and averaged by 1-km^2 grid cells. However, the current dataset is relatively recent, only covers a portion of the Bay, and peer-review validation is pending. Continued development of the remote sensing product and expansion to cover the entire Bay would enhance this data source.

Despite the relatively short temporal coverage, this data source possesses high spatial and temporal resolution, as well as robust scientific methods. In addition, NOAA has indicated that retroactive expansion of the dataset back to 2002 might be possible. Satellite data can be compared with *in situ* point data to confirm data quality. While a method has been developed for remote monitoring (a system of averaging grid squares), no method has been selected to aggregate *in situ* data.

Source description: Daily water temperature measurements obtained by satellite and averaged by 1-km^2 grid cells.
Source agency: NOAA National Environmental Satellite, Data, and Information Service (NESDIS).
Source access: NOAA-NESDIS (2023)
https://eastcoast.coastwatch.noaa.gov/time_series_cd.php
Source contact: Ron Vogel, NOAA, ronald.vogel@noaa.gov
Temporal Coverage: 2008-present (potential to stretch back to 2002)
Frequency: Data collected several times per day and rolled up into daily means
Spatial scale/resolution: 1 km^2
Applications: Status, Trends, Model development/calibration/verification

Tidal: Secondary Data Resources

The Chesapeake Bay Interpretive Buoy System (CBIBS)

CBIBS has 10 buoys located throughout the Bay and key tributaries that have been in place since 2010 with continuous data collection. CBIBS provides a rich temporal resolution dataset but does not provide nearly as many sites or as many years of data as the 1984–present Chesapeake Bay Program's long-term Chesapeake Bay water quality monitoring program. Also, some stations do not collect data year-round. CBIBS data could add value in other ways, though—perhaps as a supplementary data source for a future expansion of a water temperature indicator, or for calibration to help with further refinement of satellite data algorithm interpretation methods.

Source: NOAA CBIBS (2023). Home | Chesapeake Bay Interpretive Buoy System (noaa.gov)

The buoy at the Thomas Point lighthouse

Thomas Point (Maryland) has continuous data collection back to at least 1985, and this long-term record has been extensively studied. Measurement data are readily available, but the full time series with interpolated data used to fill temporal gaps is not as accessible. While this monitoring site has the advantage of high temporal resolution, it does not offer more years of data than the CBP long-term monitoring network, and it only covers one location. However, it could add value as a standard for calibration and assessment of variability. The team that developed the satellite-based dataset has proposed using Thomas Point data to test the robustness of trends derived from both the satellite-based product and the CBP long-term monitoring network.

Source: NOAA (2023). NDBC - Station TPLM2 Recent Data (noaa.gov)

Data from long-running individual sites such as the Chesapeake Bay Laboratory (CBL) Pier at Solomons Island, the Virginia Institute of Marine Science (VIMS) pier at Gloucester Point, and Osborn Cove

These sites are frequently cited for their long-term temperature records, and they have a notable advantage over the CBP long-term monitoring program providing decades of data before 1984. CBL, for example, has collected water temperature data since 1938 (CBL 2023) while the VIMS pier dataset extends back to the 1950's (VIMS 2023). Osborn Cove is a citizen monitoring effort led by Kent Mountford which has collected data since 1979 (unpublished) but does not provide extensive spatial coverage compared to the long-term monitoring program or the satellite-based dataset. If a need arises for a metric based on a single site, these locations could be strong candidates.

Source: Data - Patuxent Sentinel: Chesapeake Biological Laboratory Pier Monitoring Program (umces.edu)
Temperature | Virginia Institute of Marine Science (vims.edu)

Chesapeake Bay Program Shallow Water Monitoring Program

Datasets start in 2001 for fixed station continuous monitoring in nearshore waters of the bay and its tidal tributaries, typically in ≤2m of water. Data density is typically 15-minute intervals. Data may not be present for a complete year each year but focused on summer seasonal monitoring evaluations. The monitoring program was designed for monitoring to occur in 3-year blocks for each station, consistent with the temporal needs of the Chesapeake Bay water quality criteria evaluations for dissolved oxygen underpinning Clean Water Act-based water quality standards attainment assessment protocols. Therefore, many datasets are short duration, however, some stations transitioned to extended duration monitoring locations and have consistent data for over 10 years.

Reference: Maryland Eyes on the Bay (2023) Eyes on the Bay: Continuous Monitoring Data Charts Query (maryland.gov), Virginia VECOS - VIMS (2023). http://web2.vims.edu/vecos/

Community Science: The Chesapeake Monitoring Cooperative's Chesapeake Data Explorer

The Chesapeake Monitoring Cooperative (CMC) connects Community Science initiatives across groups and regions in order to amplify voices and enhance our understanding of the health of the Chesapeake Bay watershed. To accomplish this, the CMC provides technical, programmatic, and outreach support in order to integrate volunteer-based water quality and macroinvertebrate monitoring data into a centralized data hub, the *Chesapeake Data Explorer*. These data are publicly available, shared with and used by the Chesapeake Bay Program to assess the health of the Chesapeake Bay and watershed.

As of August 4, 2021, there were over 435,000 water quality data records on file within the database; most are recent data in the last decade, point samples, and a subset are bay water temperature. Data are identified by method and quality assurance level using the CMC Tiered Framework and are owned by the data provider(s) and not the Chesapeake Monitoring Cooperative. Data users are responsible for properly citing the original data provider (Note: Contact information for data providers can be found through links on the CMC's Chesapeake Data Explorer website), and responsible for using provided data in a manner consistent to the quality assurance of the provided data.

Source: CMC (2023). Home Page (vims.edu)

The maturation of the Chesapeake Monitoring Cooperative has demonstrated the utility and the importance of citizen science and alternative monitoring data. Investments in citizen science have helped generate new data streams that can support enhanced analyses of Bay health and reduce the uncertainties of present assessments.

Chesapeake Bay Sentinel Site Cooperative (CBSSC)

There are 11 core sites. Datasets vary by location. Each Chesapeake Bay Sentinel site collects long-term data on marsh elevations, water levels, water quality, emergent vegetation, and weather. A sentinel site as defined by NOAA, is "an area within the coastal and marine environment that has the operational capacity for intensive study and sustained observations to detect and understand changes in the ecosystems they represent". The CBSSC extends from the mouth of the bay just north of Virginia Beach to the bay's source, east of Havre de Grace, Maryland, where it meets the Susquehanna River. Some locations have datasets dating back to the 1970s.

Source: Wilkins, S. and A. Phelps. 2017. Chesapeake Bay Sentinel Site Cooperative: Data and infrastructure inventory summary report. (chesapeakebayssc.org)

Chesapeake Bay National Estuarine Research Reserve

At least 3 locations in Maryland where continuous monitoring data have been collected for extended periods.

Source: NOAA NERRS. 2023. National Estuarine Research Reserve System (noaa.gov)

NOAA National Data Buoy Center (NDBC)

This program is part of NOAA's National Weather Service. It designs, develops, operates, and maintains a network of data collecting buoys and coastal stations. NDBC provides hourly observations for about 90 buoys and 60 Coastal Marine Automated Network stations. All stations measure wind speed, direction, and gust; atmospheric pressure; air temperature; sea surface temperature and wave height and period.

Source: NOAA NDBC 2023. https://www.ndbc.noaa.gov/

E. EVALUATION

Understanding water quality status and trends in water quality behavior through time are often most beneficial with datasets that have long term records (i.e., 10 or more years). Trends analysis frequently uses simple linear regression as a first approximation to explain change over time while non-parametric Mann-Kendall trend tests have also been applied (Ashizawa and Cole 1994, Webb and Nobilis 1995, Durance and Ormerod 2007, Kaushal and others 2010). These statistical tests can be used to determine any differences in the significance of trends. Tidal trend tests have recently matured into using Generalized Additive Models (GAMs) (Lefcheck and others 2017, Murphy and others 2019, Testa and others 2019). Additional verification of trends and driving factors include Bayesian dynamic linear models (DLMs) (Wagner and others 2017), Weighted Regressions on Time, Discharge, and Season (WRTDS) (Hirsch and others 2010) and Process Guided Deep Learning (Zwart and others 2021) that explore the effects of discharge, land use, air temp, and groundwater on trend patterns (Briggs and others 2018).

Data resource quality was evaluated for 1) assessing status; (2) computing trends, and (3) considerations for STAC workshop information support (i.e., issues, questions, and potential recommendations) are summarized (Table 1). Items labelled TBD (To Be Determined) acknowledges the state of the review process such that some datasets already have strong histories of use in status and trends evaluations while other datasets represent new opportunities pending the form of information needs in developing a particular indicator.

Table 1. Datasets evaluated for their quality to support status, trend, or informational support needs in the CBP STAC Rising Temperature Workshop.

Dataset	Primary or secondary	Assessing status	Computing trends	Considerations: Quality, accessibility, considerations of issues, questions, Recommendations

Chesapeake Nontidal Network	Secondary	Watershed-wide	Older data yes, (Rice and Jastram 2014).	Data were discrete at the time of sampling, are presently not easily accessed but will be available through the data release. Sampling protocol may not be favorable over the program as temperature data was an ancillary measure.
UV_Chesapeake Monitoring Cooperative	Secondary	Watershed-wide, supplemental	TBD	Data are accessible. Data accessed through CBP Data Hub rather than Chesapeake Data Explorer have been through QA filters. Relatively few data have been collected at sites with sustained sampling design.
Chesapeake Bay long-term water quality monitoring program	Primary	Baywide	Yes – published assessments, established techniques	Annual program, consistent methods, consistent funding support for sustaining a physical water temperature indicator. May not have temporal coverage for connecting ecological impacts depending on interest for a management utility-based indicator.
Satellite-based Assessment	Primary	Baywide	Yes – published	Annual program, consistent methods per satellite, when satellites change

			assessments, established techniques	then calibration to historical assessment likely needed. Still working on gaining reliable data in tributaries.
The Chesapeake Bay Interpretive Buoy System (CBIBS)	Secondary	Mainstem bay potential	Exploratory	Supplemental dataset
The buoy at the Thomas Point lighthouse	Secondary	Local	Exploratory	Supplemental
Pier data UMCES-CBL and VIMS; Osborn Cove citizen data	Secondary	Local	Yes	Local, long time series have demonstrated warming consistent with regional, national and global trends. Understand how changes are affecting small local areas, if at all, compared to larger tidal water.
Chesapeake Bay Shallow water monitoring program	Secondary	Local, research support	Local stations with extended (>5 year) time series	Dataset needs to be filtered for longest-term time series with continued operations expected into the future. Breck Sullivan has done some such filtering and continued comparison of water temperature in shallow waters compared to Open Water long-term monitoring stations. Need to understand impacts of near shore characteristics on shallow water.
Community Science	Secondary	TBD	TBD - Exploratory	New program. Supplemental consideration for indicators of status, assessments of trends at this time depending on location and duration of dataset.
Chesapeake Bay Sentinel Site Cooperative	Secondary	TBD	TBD	TBD
Chesapeake Bay National Estuarine Research Reserve	Secondary	TBD	TBD	TBD (Still needs to be evaluated; some monitoring data being used in Fish GIT Spring Warming Indicator)
National Oceanic and Atmospheric Administration's National Data Buoy Center	Secondary	TBD	TBD	TBD (Still needs to be evaluated; some monitoring data being used in Fish GIT Spring Warming Indicator)

Challenges for Enhancing Monitoring Networks

Despite the large amount of watershed and tidal temperature data available, it is thus far challenging and expensive to combine the various data sources into a multiagency dataset for secondary use (e.g., climate change assessment, etc.). Nationally, the economic loss of ambiguous legacy water quality data that is either unreliable, poorly documented, and otherwise unusable) was estimated to be $12 billion (Sprague and others 2017). Collaborative efforts toward shared and reliable water quality datasets across agencies have the potential to improve the scientific basis for decision-making (Clune and Boyer 2020), however, comparability of temperature datasets among so many agencies is challenging due to various sampling designs, equipment, quality assurance, and measurement methods. Interagency committees on water information can bring together stakeholders and serve an advisory role for sharing recommended sampling, analysis, and metadata protocols, and develop a plan to resolve issues for better secondary use of data (Clune and Boyer 2020). Reliable (i.e., QA supported) datasets with a shared defined data entry format can help regional, state and local efforts in shared development of many analysis endpoints such as status and trends assessments, environmental modeling, water quality criteria development and evaluation, impaired water designations, and conservation planning.

The Scientific Technical Assessment and Reporting Team (STAR) listed the condition of the Chesapeake Bay Program tidal water quality monitoring network as “fair” during the August 2020 SRS quarterly review to the CBP Management Board. The nontidal network has previously been described as “good” (USEPA 2003). Recommended (i.e., most desirable) levels of support and sustainability were previously outlined for CBP tidal and nontidal monitoring networks (USEPA 2009). However, in the scope of this review, additional datasets that reference other networks have variously become established, sustained, modified and grown, and represent opportunities for use in water quality status and trend assessments, indicator development, model development, model calibration and verification, and other analyses.

Network enhancements may occur with more stations, new sensors, new partners, and new approaches. Research often demonstrates the opportunity to apply any such enhancement. However, operationalizing any of these enhancements is more than just acquiring new technology or recognizing a viable means of acquiring new data. Considerations and challenges include (1) the need to establish a useful sampling design to accommodate such additions, (2) the infrastructure for collecting and processing data, (3) the protocols for instrument use agreed upon and approved, (4) approved QA/QC plans for equipment maintenance and data integrity checks, (5) data collection decisions on location and frequency, (6) data storage needs and data storage stewards chosen, (7) sample handling/sensor data interpretation, and (8) analysis and reporting. Uncertainty in decisions for any one item in the list of needs may limit the adoption of new data collections, their use and availability.

Funding remains a fundamental management challenge for sustaining existing operations of networks as well as for enhancing the capacity to monitor. Despite this common annual challenge to long-term monitoring programming, many of the programs referenced are balanced by consistent support, providing substantial, valuable, time series from individual sites and have network coverage over the bay or watershed. However, annual cost of living adjustments, infrastructure aging and partner capacities to sustain support represent examples of vulnerabilities that challenge program sustainability each year. The focus on sustaining existing network operations against the impact of vulnerabilities frequently limits investments to pursue network enhancements.

Reduced capacity of the long-term monitoring program has and will continue to directly result in (1) fewer samples collected and processed in the traditional tidal water quality monitoring program (2) fewer samples collected at some stations in some seasons in the watershed, (3) elimination of stations in the watershed, (4) elimination of programs used to evaluate attainment of water quality criteria for standards attainment assessment in the Bay, (5) elimination of staff support, i.e., total FTE's supported by one state's grant is declining as function of less funding available for monitoring activities, and (6) neglected infrastructure investment – i.e. losing operation of boat which means a state must use some other, more expensive option to collect the data outlined in their Statement of Work.

The implications of reduced monitoring results to inform our analyses include:

- Greater uncertainty toward assessing water temperature trends.
- Greater uncertainty toward assessing the impact of rising water temperatures on ecological resources.
- A longer time to demonstrate progress and achievement of success.
- No dedicated "rainy day fund" to address unexpected costs each year – e.g., extra sampling needed in the event of a major event in the Bay like an oil spill, a hurricane induced high flow event, etc.

Capacity to Monitor

Most programs with a long-term history of data collection have established funding streams to sustain efforts into the future. Such datasets are high value targets for use in applications such as status and trend analyses, indicator development, and model development, calibration, and verification. Regarding program and network enhancements that may fill data collection gaps identified by the CBP Scientific and Strategic Research Framework (SSRF), or provide potential solutions to explore addressing stressors affecting capacity in the monitoring programming, the Chesapeake Bay Program community provided input into options for water quality monitoring capacity building, the most comprehensive summary available has been documented in the recent Chesapeake Bay Program's 2021-22 PSC Monitoring Program Review report (Chesapeake Bay Program 2022).

As part of the CBP work to incorporate additional data streams into existing assessments or to support new assessment needs, especially real-time and other new high temporal data streams, there is a need to continue refining analyses to improve understanding of major drivers of temperature change. Further insights are needed to better distinguish the response of impacted resources around the watershed, within and across tidal tributaries, and along the mainstem Bay. Participants in the first STAC Rising Water Temperature Cross-Workgroup meeting event highlighted the need for better tools for analysis and reporting using the diversity of existing data collections in addition to the need for more data resources. They also prioritized the need for investment in relevant monitoring information around resource impacts in response to temperature change and management actions such as the response to seagrass and fish distributions. Continued collaboration and engagement with science providers will produce successful research and analysis with reliable monitoring data that will move progress forward on addressing key management questions and foster targeted management actions to accelerate progress in the restoration of Chesapeake Bay and its watershed.

F. BIBLIOGRAPHY

References Cited

Ashizawa, D and Cole, J.J. 1994. Long-term temperature trends for the Hudson River: a study of the historical data. Estuaries 17: 166–71.

Briggs, M., Z. Johnson, C. Snyder, N., Hitt, B. Kurylyk, L. Lautz, D. Irvine, S. Hurley, and J. Lane. 2018. Inferring watershed hydraulics and cold-water habitat persistence using multi-year air and stream temperature signals. Science for the Total Env. Sep 15;636:1117-1127. DOI: 10.1016/j.scitotenv.2018.04.344

Chesapeake Biological Lab (CBL). 2023. [Data - Patuxent Sentinel: Chesapeake Biological Laboratory Pier Monitoring Program (umces.edu)]

Chesapeake Bay Program (CBP). 2017. Excel spreadsheet: Monitoring networks 9-21-17 https://www.chesapeakebay.net/who/group/scientific_and_technical_analysis_and_reporting

Chesapeake Bay Program (CBP). 2018. Climate Change Indicators for the Chesapeake Bay Program: An Implementation Strategy. Submitted to: Chesapeake Bay Program 410 Severn Avenue, Suite 109 Annapolis, MD 21403. Submitted by: Eastern Research Group, Inc. 2300 Wilson Blvd, Suite 350 Arlington, VA 22201. Revised Edition July 13, 2018. https://www.chesapeakebay.net/channel_files/31218/indicator_implementation_plan_-_revised_-_07-13-18.pdf

Chesapeake Bay Program (CBP). 2020. Water Quality Standards Attainment and Monitoring Outcome Narrative Analysis completed by the Monitoring Team at the Chesapeake Bay

Program through the Strategic Review System. Submitted to: Chesapeake Bay Program 410 Severn Avenue, Suite 109 Annapolis, MD 21403. https://www.chesapeakebay.net/documents/22046/wqsam_post_quarterly_review_logic__action_plan_2021.2022.pdf

Chesapeake Bay Program (CBP). 2023. Data Hub. DataHub (chesapeakebay.net)

Chesapeake Bay Program (CBP). 2022. Enhancing the Chesapeake Bay Monitoring Networks: A report to the Principals' Staff Committee. FINAL_Enhancing_the_Chesapeake_Bay_Program_Monitoring_Networks_A-Report_to_the_Principals_Staff_Committee_10.13.22-1.pdf (d18lev1ok5leia.cloudfront.net)

Chesapeake Monitoring Cooperative (CMC). 2023. Chesapeake Data Explorer database. https://cmc.vims.edu/#/home

Clune, J.W., J.K. Crawford, W.T. Chappell, and E.W. Boyer. 2020. Differential effects of land use on nutrient concentrations in streams of Pennsylvania. Environmental Research Communications, 2(11):115003.

Clune, J.W., J.K. Crawford, E.W. Boyer. 2020. Nitrogen and Phosphorus Concentration Thresholds toward Establishing Water Quality Criteria for Pennsylvania, USA. Water 12(12):3550.

DeCicco, L., R. Hirsch, D. Lorenz,, J. Read, J. Walker, L. Carr, D. Watkins, D. Blodgett, M. Johnson. 2022. dataRetrieval: Retrieval functions for USGS and EPA hydrologic and water quality data: a collection of functions to help retrieve U.S. Geological Survey (USGS) and U.S. Environmental Protection Agency (EPA) water quality and hydrology data from web services. https://rdrr.io/cran/dataRetrieval/.

Durance, I. and S. Ormerod. 2007. Climate change effects on upland stream macroinvertebrates over a 25-year period. Glob Change Biol. 13: 942–57.

Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, and R.L. Wingate. 2010, Rising stream and river temperatures in the United States: Frontiers in Ecology and the Environment. 8(9):461–466.

Lefcheck, J.S., D.J. Wilcox, R.R. Murphy, S.R. Marion, and R.J. Orth. 2017. Multiple stressors threaten the imperiled coastal foundation species eelgrass (*Zostera marina*) in

Chesapeake Bay, USA. Global Change Biology 23:9. https://doi.org/10.1111/gcb.13623

Maryland Eyes on the Bay. 2023. Eyes on the Bay: Continuous Monitoring Data Charts Query (maryland.gov)

Murphy, R.R., E. Perry, J, Harcum, and J. Keisman. 2019. A Generalized Additive Model approach to evaluating water quality: Chesapeake Bay case study. Environmental Modelling and Software 118:1-13. doi: https://doi.org/10.1016/j.envsoft.2019.03.027.

National Water Quality Monitoring Council. 2020. Water Quality Portal (WQP), accessed at https://waterqualitydata.us/.

NOAA. 2023. NDBC - Station TPLM2 Recent Data (noaa.gov)

NOAA CBIBS. 2023. Home | Chesapeake Bay Interpretive Buoy System (noaa.gov)

NOAA NDBC 2023. https://www.ndbc.noaa.gov/

NOAA NERRS. 2023. National Estuarine Research Reserve System (noaa.gov)

NOAA-NESDIS. 2023. https://eastcoast.coastwatch.noaa.gov/time_series_cd.php

Rice, K.C. and J.D. Jastram. 2015. Rising air and stream-water temperatures in Chesapeake Bay region, USA. Climatic Change 128: 127–138. https://doi.org/10.1007/s10584-014-1295-9

Sprague, L.A., G.P. Oelsner, and D.M. Argue. 2017. Challenges with secondary use of multi-source water-quality data in the United States. Water Research 110: 252–261.

Testa, J.M., R.R. Murphy, D.C. Brady, and W.M. Kemp. 2018. Nutrient- and climate-induced shifts in the phenology of linked biogeochemical cycles in a temperate estuary. Frontiers in Marine Science. 5:114. doi: 10.3389/fmars.2018.00114

USEPA. 2003. Ambient Water Quality Criteria for dissolved oxygen, water clarity and chlorophyll a. U.S. EPA. https://www.chesapeakebay.net/content/publications/cbp_13142.pdf

USEPA. 2009. Monitoring Re-Alignment Action Team Final Report to the CBP Management Board. https://www.chesapeakebay.net/channel_files/21466/mrat_final_report_to_the_cbp_ management_board_2009.pdf

Virginia Institute of Marine Science (VIMS). 2023. VECOS. http://web2.vims.edu/vecos/

Wagner, T., S.R. Midway, J.B. Whittier, D.T. Jefferson, and C.P. Paukert. 2017. Annual changes in seasonal river water temperatures in the Eastern and Western United States. Water 9(2): 90. https://doi.org/10.3390/w9020090

Webb, B.W. and F. Nobilis. 1995. Long-term water temperature trends in Austrian rivers. Hydrology Sci. J. 40: 83–96.

Wilkins, S. and A. Phelps. 2017. Chesapeake Bay Sentinel Site Cooperative: Data and infrastructure inventory summary report. Microsoft Word - CBSSC_Data&InfrastructureSummaryReport_FINAL.docx (chesapeakebayssc.org)

Wilson, D. 2021. Chesapeake Bay dissolved oxygen profiling using a lightweight, low-powered real-time inductive $CTDO_2$ mooring with sensors at multiple vertical measurement levels. A report to the Chesapeake Bay Trust. https://cbtrust.org/wp-content/uploads/16793_Caribbean-Wind_Final- Report_Jan2021.pdf

Zwart, J., S. Oliver, D. Watkins, J Sadler, A. Appling, H. Corson-Dosch, X. Jia, V. Kumar, and J. Read. 2021. Near-term forecasts of stream temperatures using process-guided deep learning and data assimilation. EartArXiv. 27pp. https://doi.org/10.31223/X55K7G