

A Community Risk Assessment of Flooding and Heat Hazards in the Baltimore Metropolitan Area



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Executive Summary

Coastal communities are exposed to numerous climate-related hazards, all of which are projected to increase in intensity and frequency in the coming decades. The impacts of these hazards depend on structural and social factors that make coping and recovery more difficult for some communities than others. The study area of the Baltimore metropolitan area—Baltimore City and the five surrounding counties—exhibits all of these dynamics. The region faces increasing pressure from water-related hazards such as storm surge, sea level rise, and stormwater flooding. Given the Chesapeake Bay’s extensive coastline, managing floodwaters is a key priority moving forward. The varied and dense populations of the Baltimore metropolitan area create a high risk of cascading and compounding hazard events where multiple vulnerabilities intersect with climate hazards.

This report follows in the tradition of the National Centers for Coastal Ocean Science Risk Assessment Portfolio, addressing the need for mid-scale assessments between national evaluations and community adaptation projects. It also serves as a comprehensive reference for climate-related hazards and associated vulnerabilities and exposures. The first half of the report presents the collected data one component at a time. These components were determined through stakeholder consultation, during which research questions were prioritized, and a gap analysis of available data was conducted. The second half of the report addresses selected research questions using a geospatial layering technique called bivariate choropleth mapping. This type of work is increasingly required by funding programs to qualify for adaptation grants, and this report can serve as a reference for groups applying for such programs, foundational research for adaptation planning, as well as for education and outreach about handling multiple climate risks simultaneously.

Assessment components: The research team incorporated population metrics of the region, including population density and projected population change. A structural exposure index, which includes critical infrastructure, educational and financial institutions, emergency management services, hazardous waste facilities, and community amenities, was developed. An ecosystem services valuation index was also incorporated, estimating dollar values of atmospheric pollution removal, carbon sequestration, groundwater recharge, nitrogen removal, flood prevention and stormwater mitigation, wildlife habitat and biodiversity, and surface water protection. Although a combined flooding risk index was initially requested, it is presented in three separate components for clarity: (1) a stormwater flooding index that incorporates indicators of flow accumulation, rainfall intensity, geology, land use, slope, elevation, and drainage network proximity; (2) projections of 2- and 5-ft sea level rise; and (3) storm surge estimates for Category 2 and Category 4 hurricanes. The final component is an urban heat index.

The report concludes by analyzing combinations of these components. More detailed combinations are used to explore the potential for nature-based infrastructure to protect key community resources. Finally, thresholds within component data ranges are examined. Key findings are as follows:

- Stormwater flooding poses a threat not only through destructive flows but also in areas where water accumulates. By incorporating stormwater into the analysis of flooding risk, the focus shifts from the shoreline to the watershed, where stormwater can accumulate and flow through developments, causing damage and potentially delivering polluted water to Chesapeake Bay.
- Urban heat is a critical issue in the study area, driven by the concentration of impervious, heat-absorbing surfaces such as asphalt and concrete, and limited tree cover and green space. These dynamics affect heat at a very small scale, and adaptation measures should be considered at a similarly small scale.
- Given the historic nature of both Baltimore and Annapolis, a large proportion of commercial and cultural landmarks are located along the waterfront, placing them in the risk zone for sea level rise and storm surge. These pieces of critical infrastructure serve areas throughout the study region, so the structural inventory presented here includes not only the infrastructure itself but also the transportation routes that connect to it.



Credit: Emma Warnick

Part 1: Introduction and Motivation

1.1 Portfolio Overview

Coastal populations face risks from erosion, storms, and flooding. These and other natural hazards, including wildfires, droughts, heavy precipitation, and heat waves, are intensifying (Lee et al., 2023). Impacts from these hazards are unevenly distributed across the country due to differences in topography, risk profiles, and local influences (Frazier et al., 2014).

Risk and exposure for communities depends on various factors that extend beyond predicted hazard maps. Although national tools exist to map hazard exposure and resilience to those hazards (e.g., National Risk Index [Federal Emergency Management Agency, 2024]), they often lack the resolution or scale needed for meaningful regional or local action. These metrics typically rely on data available across the entire country, often excluding state and local datasets, which can obscure critical local nuance.

To address these information gaps and help coastal communities assess and document their risks from environmental hazards, the National Centers for Coastal Ocean Science (NCCOS) has conducted place-based integrated community risk assessments since 2014 (Fleming et al., 2017, 2022; Freitag et al., 2022; Messick et al., 2016; Miller et al., 2023). Assessment locations are selected based on presidential directives and national policy considerations in coordination with partner needs and capacity constraints. Each assessment defines risk as the potential for adverse consequences of a climate-related hazard (U.S. Climate Resilience Toolkit, 2021). Researchers developed a transferable, integrated community risk assessment framework (Figure 1), examining social, structural, and environmental factors in relation to environmental variability and impacts. The framework builds on methods from Wu et al. (2002), relying primarily on secondary data and supplementing with stakeholder-derived primary data to develop risk indicators and indices (Fleming et al., 2022). These indices are then layered with hazard indices, creating maps that highlight areas and communities at increased risk. Iterative partner engagement through advisory committees, workshops, and follow-up correspondence is essential to ensuring that each assessment is tailored to local needs for actionable project outcomes. For more information on the NCCOS community risk assessment portfolio approach, please see the portfolio webpage:

<https://coastalscience.noaa.gov/project/programmatic-execution-of-nccos-risk-assessments/>

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Partner engagement	Indicator development	Assess vulnerability and hazard	Assess risk	Conduct place-based analysis	Develop and release products
Determine project advisory committee. Hold workshop meeting(s) to determine project goals and prioritize local needs.	Gather local and national data to develop indicators and indices, using partner and stakeholder input.	Develop maps of each vulnerability (or exposure) and hazard index. Present for key partner feedback.	Spatially assess risk by intersecting vulnerability (and/or exposure) with hazard. Present for key partner feedback.	Develop additional place-based indices and intersect with other assessment maps. Present for key partner feedback.	Develop products. Present findings and products to full list of partners and stakeholders. Revise and finalize.

Figure 1. NCCOS community risk assessment framework steps.

The Baltimore metropolitan area assessment is the sixth in the NCCOS risk assessment portfolio. This project returned to Maryland, where the first assessment was conducted for Oxford, MD (Messick et al., 2016). The Oxford assessment raised key questions about the framework’s application to urban settings, its integration with ongoing resilience and adaptation efforts, and its role in supporting climate adaptation at multiple scales. This second assessment was conducted in collaboration with two original key partners: Maryland Sea Grant and Maryland Department of Natural Resources.

1.2 Study Area

The study area (Figure 2) was designed to focus on the city of Baltimore as well as include the communities that are connected to Baltimore City’s resources. The city’s urban development extends beyond the city’s jurisdictional boundaries, with some properties straddling the line between the city and the neighboring county. In addition, people from surrounding suburban towns and exurban areas often commute to Baltimore for work, are dependent on the port for their business needs, or rely on the infrastructure offered by the city such as hospitals, wastewater treatment, and universities. Project stakeholders were asked to choose, based on these jurisdictional dynamics, which counties should be included in a risk assessment of the Baltimore region, and the five immediately adjacent counties were prioritized (Baltimore, Harford, Howard, Anne Arundel, and Queen Anne’s Counties).

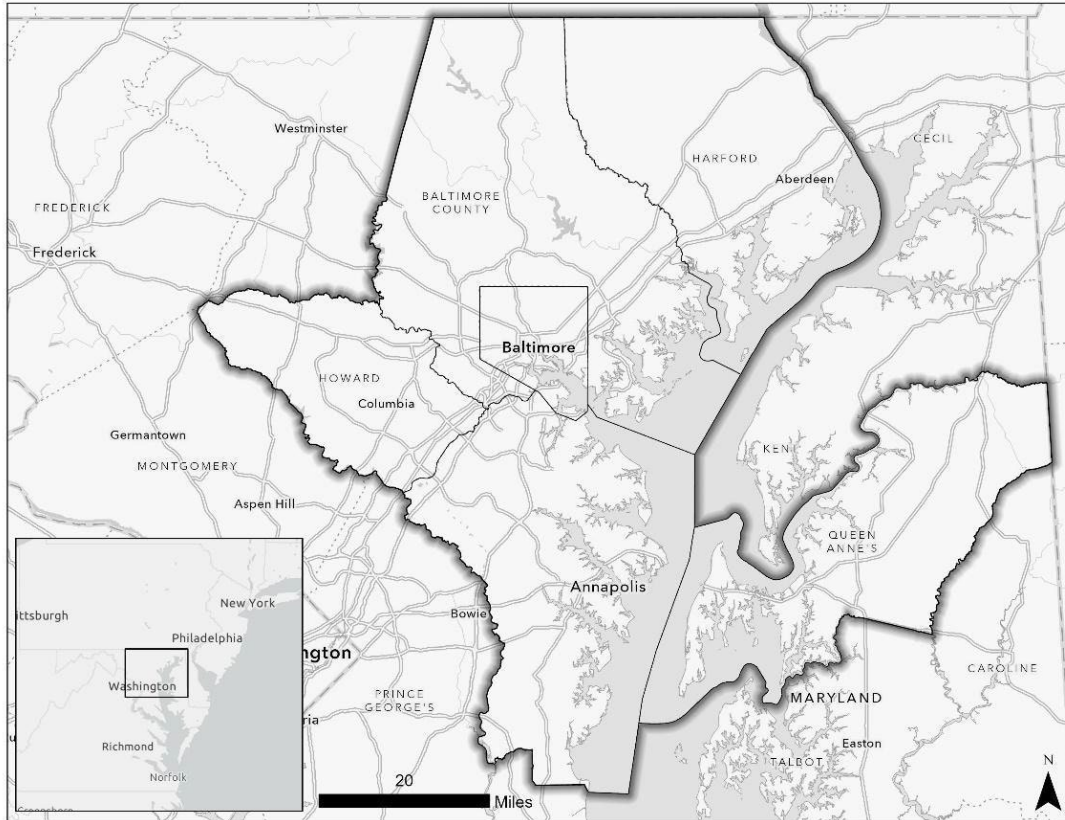


Figure 2. The study region of Baltimore and the five surrounding counties.

The study area is further subdivided into a total of 1,967 census block groups as the units of analysis; those containing the Aberdeen Proving Ground have been omitted because much data are unavailable or suppressed there for national security reasons.

1.2.1 Climate Profile

The study area lies within the northern temperate zone. Unless explicitly stated otherwise, climate summaries listed here refer to the study area geography. Between 1991 and 2020, average weather conditions (NOAA National Weather Service, n.d.) reveal hot, humid summers, with average highs of 88.8°F and extreme days above 100°F. These high temperatures are even more intense and prolonged over impervious surfaces, which cover 13% of the study area (Chesapeake Conservancy et al., 2022). Winters are relatively mild with occasional snow, averaging 18.4 inches, annually. The mean minimum temperature is 25.4°F, and for three months each year, daily lows routinely fall below freezing (NOAA National Weather Service, n.d.). Precipitation varies seasonally, from a low of 2.9 inches in February to a peak of 4.48 inches in July (NOAA National Weather Service, n.d.). Over the past century, Maryland has experienced a 5% increase in average rainfall and a 2°F rise in average temperatures (Baltimore Office of Sustainability, 2023).

Chesapeake communities are at heightened and increasing risk for flooding and coastal hazards (Strain et al., 2014). Sea level rise and storm surge threaten both wildlife and human communities, with potential to

disrupt ecosystem functions through changes in salinity and water circulation in Chesapeake Bay (herein, also referred to as “the Bay”; Cronin, 2013). Changing environmental conditions are expected to intensify the severity of storms (Chung et al., 2021), while rising sea levels and subsiding land increase the likelihood of both coastal and inland flooding, and potential flooding extent increases with severity of the predicted emissions scenario (Boesch et al., 2023). Baltimore City alone has 61 miles of shoreline and has experienced 75 incidents of inundation flooding recorded at the Baltimore tide gauge in the last decade, a large increase compared to previous decades (Conkwright, 2003; Maryland Department of Natural Resources, 2024b; NOAA Tides and Currents, 2025).

1.2.2 Ecological Profile

The Chesapeake Bay is a drowned river valley developed in the Pleistocene era and later shaped through the rise and fall of sea level throughout glacial cycles. During interglacial periods, sediment accumulation enlarged the inter-river peninsulas and carved regional scarps (Hobbs, 2004). The Bay now functions as a tidal inlet populated by estuarine ecosystems and a significant human population historically dependent on estuary resources and Bay navigation. The study area is situated on top of several of these inter-river peninsulas.

The region is also an ecotone between the southern and northern biomes, leading to a mix of forest types and relatively high biodiversity with 27 rare ecological communities (Maryland Department of Natural Resources, 2016). Chestnut blight and warming temperatures are transitioning forest land to a Southern pine-oak ecotype. The human population in cities and on farms have also significantly fragmented the forest landscape. Like most of the temperate deciduous forestlands of the mid-Atlantic, these forests and forested wetlands are structured by a large white-tailed deer population and beavers altering water flow. Populations of these ecosystem engineers are also changing; deer are now overpopulated and encroach upon suburban landscapes, while beaver populations have recently begun to recover as a result of active wetland management (Payne, 1989; Roden-Reynolds et al., 2022).

Aquatic communities begin with wetland, shrubland, and marshland, and extend through the Bay’s shallow waters, where oysters and submerged aquatic vegetation structure the habitat, serving as keystone species. These habitats also provide important nursery grounds for Bay fish species, which support a fishery highlighting blue crabs, striped bass, and oysters (Hengst et al., 2010).

1.2.3 Socio Economic Profile

The study area is divided into five counties (Anne Arundel, Baltimore, Harford, Howard, Queen Anne’s) and one independent city (Baltimore City), with a total population of 2,691,090 (U.S. Census Bureau, 2021). The most densely populated area in the study geography is Baltimore City, with 565,239 people (U.S. Census Bureau, 2023) and 21% of the total study population.

The study area includes two other cities that serve as economic and social hubs as well as Baltimore: Columbia and Annapolis. In Columbia, 41% of residents live in single-family detached homes (Dembner et al., 2012). The City of Annapolis has a large proportion (46.5%) of non-family households, most likely due to the higher percentage of individuals over the age of 65 and between the ages of 18–34 (Burkholder and Ali,

2021). Residents over the age of 65 show the highest growth rate in the city, with a 48.8% increase between 2010–2021 (Burkholder and Ali, 2021). These demographic factors are suspected to shape future population growth.

1.2.4 Infrastructure Profile

Baltimore and Annapolis both developed as port cities, with modern infrastructure shaped by long-standing maritime industries. Baltimore, founded in 1729, initially established shipping infrastructure, naval support, and critical public works projects (City of Baltimore Department of Planning, 2006). By 1930, the city's cultural institutions were founded, including several universities, libraries, and art museums dedicated for the use of all city residents (City of Baltimore Department of Planning, 2006). Baltimore is now considered a post-industrial city, in which the economic opportunities associated with industry have largely left and industrial infrastructure left behind is aging and available for re-purposing (Kahn and McComas, 2021).

Annapolis, founded in 1634, began as a shipping port and was established as the colonial capital in 1694 due to its centrality to Maryland communities along water transit routes. Oyster packing, boatbuilding, and sail making remain mainstays of the waterfront, with the addition of tourism in recent decades (McWilliams, 2011). The State House, St. Johns College, and the Naval Academy remain major landmarks and resources for the city and surrounding area.

Both cities have long-standing ties to water-dependent industries and therefore much of the infrastructure of the region is waterfront by design. Proximity to the Bay however, has both benefits and drawbacks, especially as sea levels rise; commercial districts of both cities regularly experience flooding at high tide (also known as sunny-day flooding or nuisance flooding) (Davies et al., 2022). As the population in the region has grown, a regional approach to infrastructure has emerged. Infrastructure in more recently settled counties (Harford, Howard, parts of Baltimore County) are organized around major roads rather than waterways.



Credit: Amy Freitag (NOAA NCCOS)

1.3 Project Background

1.3.1 Existing Assessments

The Baltimore region has a strong foundation of research in the resilience field stretching back for decades. A summary of this prior work is provided below. A majority of this work focused on only Baltimore City or the entire state, and many of these studies focused on a single component, primarily social or structural. These studies can serve as a means of looking at changes over time when compared with this assessment and methodologies were harmonized where possible to allow this comparison.

For structural vulnerability, Army Corps of Engineers completed a study in 2022 focused on coastal flooding in the Patapsco River after the Patapsco was identified as one of nine high-priority areas in the North Atlantic Coast Comprehensive Study (U.S. Army Corps of Engineers, 2015). They focused on regionally important critical infrastructure, including port terminals, highways (and evacuation routes), hospitals, public utilities and local airport authority facilities that are susceptible to flooding. Conclusions of the study listed options to reduce flood risk, including levees, storm surge barriers, flood proofing facilities and living shorelines around critical infrastructure locations (U.S. Army Corps of Engineers and Maryland Department of Transportation, 2024). While this study focused on the Patapsco, criteria for inclusion in the study included potential regional impact should those facilities flood during a storm.

The City of Baltimore Disaster Preparedness and Planning Project, completed in 2015, serves as a combined hazard mitigation and adaptation plan for the city and addresses demographics, critical infrastructure, and susceptibility to a wide range of hazards in chapter 4 (Baltimore Office of Sustainability, 2023). This project's methodologies served as a foundation for the structural inventory presented in this study, which expanded the listed types of infrastructure. The chapter cites Federal Emergency Management Agency's Hazus modeling to estimate economic damage to particular pieces of infrastructure found in the city should they be subject to damage by flooding, wind, earthquakes, high precipitation, and identifies neighborhoods most at risk of urban heat stress. The chapter then matches highly vulnerable infrastructure to certain types of hazards and discusses how adaptive capacity might be raised for particularly risky locations (Baltimore Office of Sustainability, 2023); summarized here are their main goals:

- **GOAL 1:** Protect the health, safety, and welfare of Baltimore City residents and visitors
- **GOAL 2:** Prevent damage to structures, infrastructure, and critical facilities
- **GOAL 3:** Build resilience and disaster prevention and planning into all programs, policies, and infrastructure (public and private)
- **GOAL 4:** Enhance the City of Baltimore's adaptive capacity and build institutional structures that can cope with future conditions that are beyond past experience
- **GOAL 5:** Promote hazard mitigation and climate adaptation awareness and education throughout the City of Baltimore
- **GOAL 6:** Become a Community Rating System (CRS) classified community¹

¹ For more information on the CRS program, see: <https://www.fema.gov/floodplain-management/community-rating-system>

Climate impacts to transportation have also received recent research attention, both in documenting exactly where transportation disruptions occur (Ikiriko, 2022) and the economic impacts of those transportation disruptions (Hino et al., 2019). The State Highway Administration has made a statewide tool for measuring potential climate impacts to state highways (Maryland Department of Transportation, 2024), which has become an often referenced resource by the risk preparedness community in the region (as reported by project stakeholders). The Maryland General Assembly has also prioritized communities for state funding programs to mitigate climate impacts and created a tool to determine where a community ranks according to their evaluation criteria (Maryland Department of the Environment, 2024).

1.3.2 Regional Gap Analysis

Despite the Chesapeake being one of the most data-rich regions of the U.S., there are still data gaps, especially for high spatial resolution data that allows the kinds of analysis and application desired by managers, especially local managers such as mayors or town resilience committees. For this type of composite study, another major gap is the expertise required to combine datasets and model outputs of differing mathematical origins. For example, there is strong desire for a combined flooding model expressed by stakeholders, literature (e.g., Wang et al. (2015), and management documents (e.g., the 2023 Baltimore City Disaster Preparedness and Planning Project). However, stormwater flooding often uses a probabilistic modeling approach based on weather data, and sea level rise and storm surge are both deterministic models based on climate projections; integration of these two approaches into one is problematic and difficult to achieve with existing methods (Wang et al., 2015).

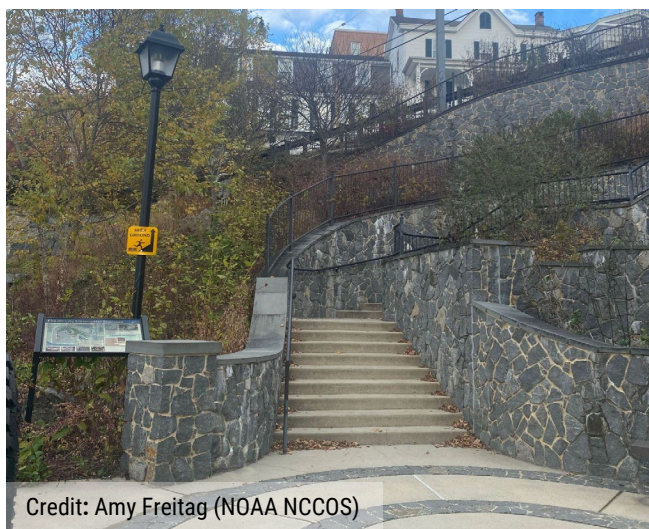
The research wish list created by project partners and stakeholders (described in the next section) showed the limits of what existing data can deliver. For example, the top research question, addressing the benefits of nature-based infrastructure and restoration projects, requires extremely high-resolution data for numerous potential benefits. Infrastructure and restoration most often happens on a single-property scale, while climate projections, economic data, and social data are generally at the census block group scale at best. Even some more direct impacts of restoration, such as the extent and power of wave attenuation services of a restored oyster reef, are not yet scientifically established (Salatin et al., 2022). Therefore, it is very difficult to determine the area affected by a restored reef, both in terms of hydrodynamics and secondary effects like cultural ecosystem services. While it may be difficult to exactly quantify the benefits of restoration, studies like Salatin et al. (2022) document some degree of benefits and demonstrate the need for further study to quantify them and determine the primary beneficiaries of these effects.

Some data gaps are due to be addressed by currently ongoing projects. A stormwater vulnerability study is underway by Michelle Miro, Krista Romita Grocholski and others following their initial report (Miro and Grocholski, 2023), which will examine the issue of data availability across the whole Chesapeake watershed. It will then synthesize vulnerability assessment approaches, identify relevant existing data sources, and highlight case study examples. Fine scale resolution data are being prioritized across a number of research areas in the watershed, most notably 1-m scale land use and land cover data by the Chesapeake Conservancy et al. (2022), and Water 2.0, the fine scale hydrodynamic network model for the country which will include culverts, fine mountain streams, and shorelines.

1.4 Partner and Stakeholder Engagement

The key partnerships of Maryland Sea Grant and Maryland Department of Natural Resources were built from existing relationships grounded in a previous risk assessment in the Choptank River Habitat Focus Area, on the Eastern Shore (Fleming et al., 2017). A larger group of stakeholders was assembled through contacting relevant parties suggested by key partners, found through existing related research, or found through one of several regional climate-related workgroups, most notably the Chesapeake Bay Program Resilience Working Group and the Baltimore Urban Waters Partnership. Both of these groups consist of federal, academic, and community group partners. To better understand relationships among this large group of stakeholders, Maryland Sea Grant held a workshop to address the nascent field of professional resilience coordinators, mapping out the social network of resilience professionals as they relate to key topics of resilience (see Appendix D for more details).

The research team met with each interested group of partners and stakeholders to discuss the research needs of the region and establish how a risk assessment can best fit with existing research and management efforts. These representatives spanned sectors (government, academic, nonprofit), expertise (resource management, community development, conservation, local planning, etc.) and scale of activity (national, regional, state, city, community). A group of 48 partners helped create a wish list (see Appendix B) of research questions that varied in topic but could generally be categorized in one of four themes: governance questions, retreat and migration questions, better population data, and better risk assessments. This wish list was then provided to stakeholders and distributed through the Resilience Working Group distribution list, who were asked to prioritize which questions should be addressed first. Results of this prioritization from 20 participants are shown in Table 1, with land use planning questions taking the lead; those highlighted are questions addressed in this assessment and serve as the location-specific questions outlined in the portfolio approach², more concretely (see section 3):



1. How does nature-based infrastructure protect community resources?
2. For components addressed in the risk assessment, where are important thresholds within the range of data?

² For more information on the portfolio, see <https://coastalscience.noaa.gov/project/programmatic-execution-of-nccos-risk-assessments/>

Table 1. Results of the research prioritization exercise. Highlighted questions are addressed in this assessment; three highlighted in green were combined into a broader tipping-points assessment.

Category (in order of preference)	Top research topic	Secondary research topic
Land use planning	Evaluate impacts of natural infrastructure and restoration efforts	Forecast when and where communities face climate-related thresholds
Better risk assessments	Map to advise communities if what they're considering is enough to meet the risks forecasted in the area	Where floodwaters are putting pressure on stormwater and wastewater systems
Retreat and migration	Are there identifiable tipping points or thresholds at which different decisions should be made, like retreat?	Spatially resolute shoreline mapping data and how they are expected to perform in future climate scenarios
Better human population data	Forecasting human patterns out to the same length of time as climate models	Are the information needs and/or tipping points different for water-dependent industries? ----- What are the impacts to the tax base if people choose retreat?

Stakeholders received quarterly updates via email on project status and some had more regular conversations with the research team (e.g., ad hoc consultations on data and methods, participating in standing workgroups together, or scheduled phone check-ins). Each newsletter requested feedback on the direction of the research, next steps, and specific questions related to the stage of the research. This feedback was critical in structuring the research.

1.4.1 Community Workshop on Thresholds

Planning for the impacts of changing environmental conditions is not a linear process of gradual adaptation. There are instances when the impacts surpass the limits of available adaptations, when social preferences and values shift to prioritize new options, or when policy incentives drive certain pathways (Adger et al., 2009). For similar reasons, during the research prioritization phase of this risk assessment, threshold-related questions were prevalent among the top identified concerns (Table 1, highlighted in green).

Different disciplines each define the concept of a threshold differently (Gardiner, 2011). The Chesapeake Bay Program Resilience Working Group convened a special session to address thresholds. The prompt for the workshop was: "Discussion topics include indicators for when adaptation strategies should shift, how to approach communities and engage with them, and sharing pitfalls and success stories on engaging with communities." This workshop used existing "tipping points," defined by the group as the point in the data

where different decisions may be required, to identify important decision criteria relevant to this risk assessment. These examples are included in relevant sections of this report identified as “decision criteria.”

A key part of the workshop discussion was how to introduce the concept of thresholds with cultural sensitivity. The majority of comments emphasized the importance of contextual awareness, recognizing community history and values, and taking the necessary time to build trust with community members before acting. A summary of this discussion is presented in Figure 3.

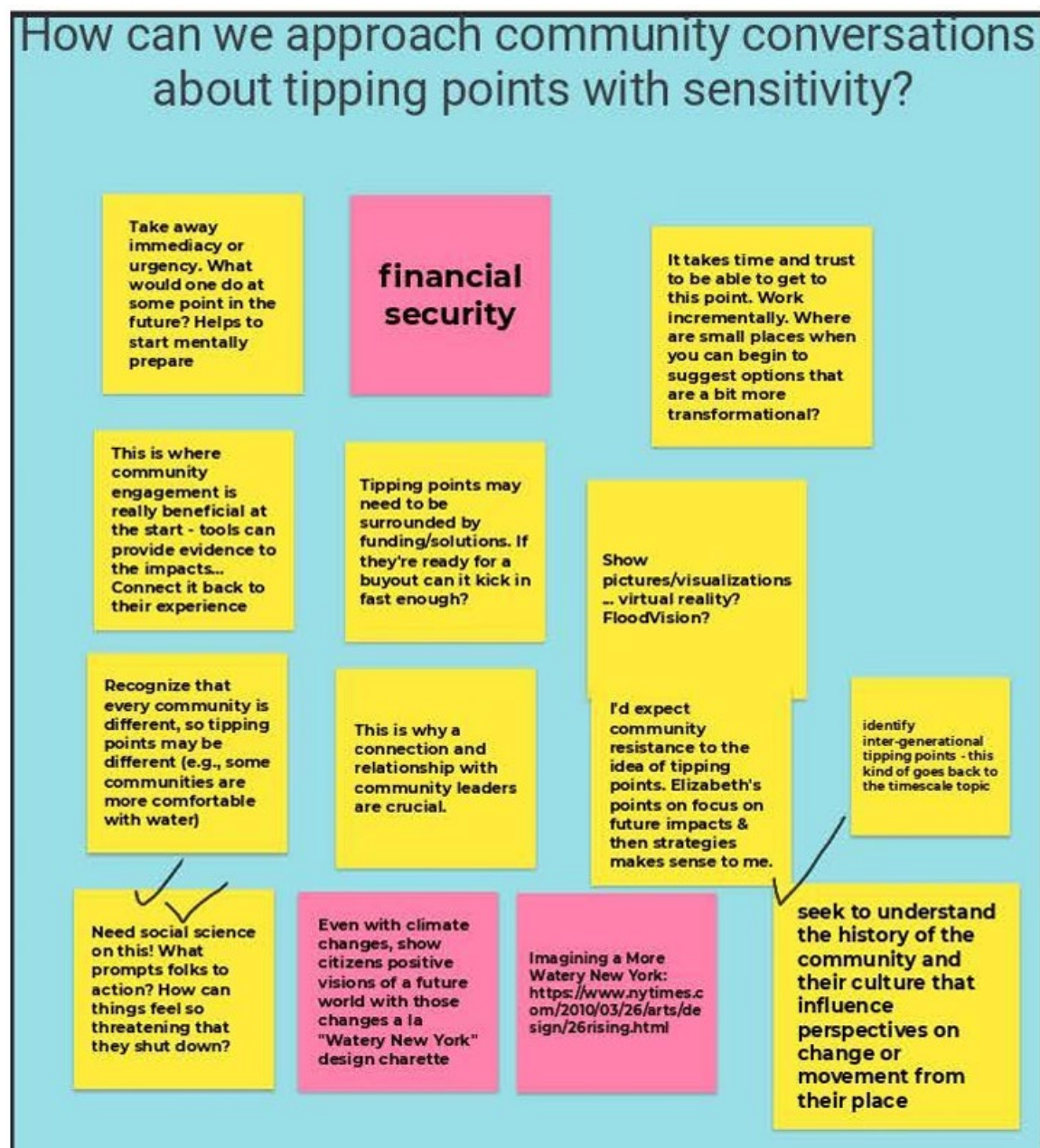


Figure 3. A screenshot of the collective brainstorming session held at the Resilience Working Group regarding how to address tipping points. Check marks indicate additional support for that box's ideas.

Within the Resilience Working Group, there is already a strong foundation of trust and rapport, so the next question was: What thresholds for the Chesapeake are identifiable? The group generated a broad range of suggestions, not all of which were actual thresholds but instead reference points from existing guidance documents for adaptation work (see Figure 4). Only a few are quantifiable for data-driven analysis: a) engineering limits of existing adaptations, b) economics of current management plans, c) public service impacts, and d) repeated loss experienced or predicted. Based on the available data for this assessment, five examples were identified to highlight points within assessment data at which decision criteria may change: a) shoreline height versus storm surge, b) critical roads vs. storm surge flooding, c) stormwater pipes versus sea level rise, d) community resources versus sea level rise, e) urban heat exceeding 90°F. These will be discussed further in the relevant assessment sections.

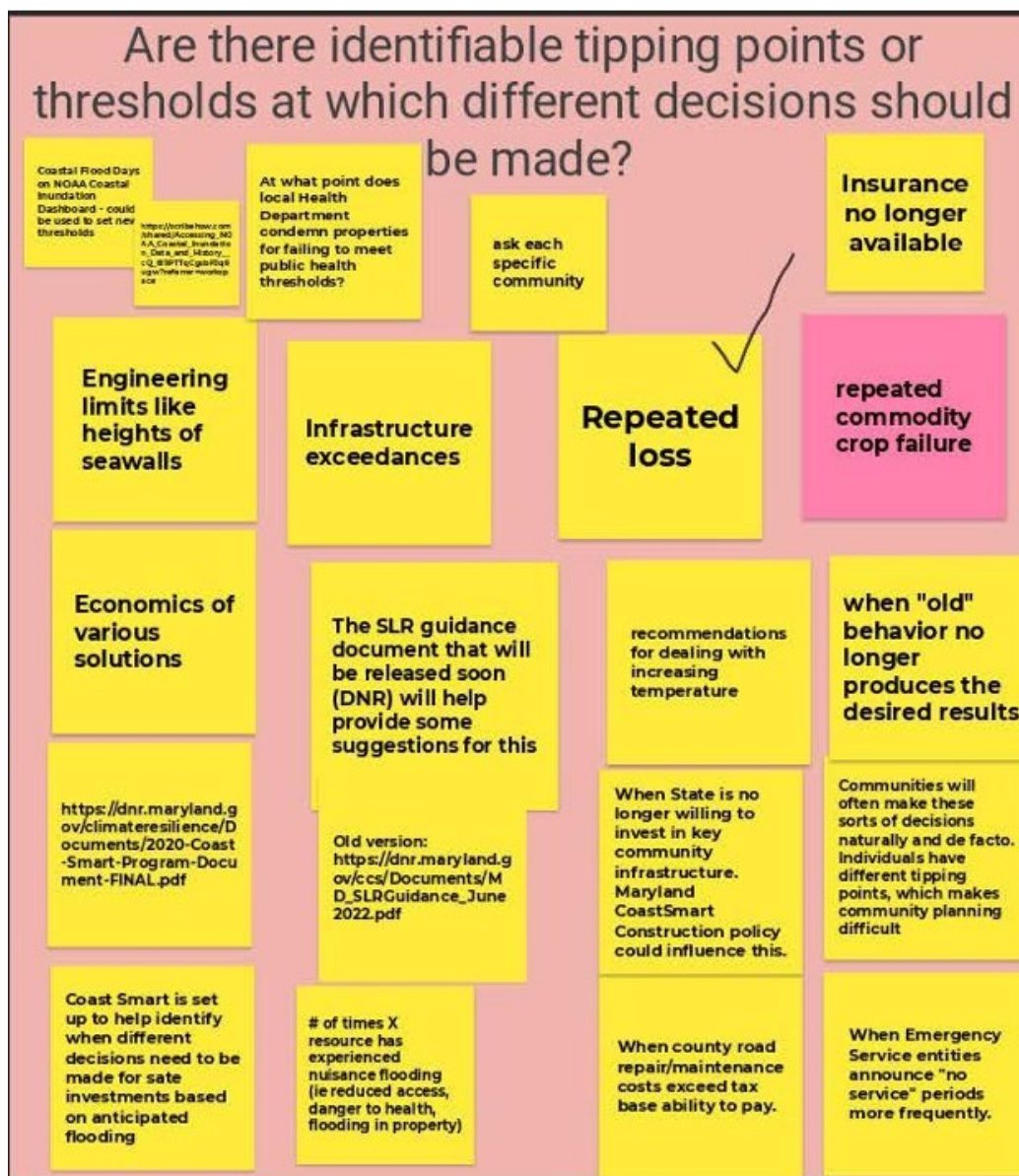


Figure 4. A screenshot of the collective brainstorming session held at the Resilience Working Group identifying tipping points. A check mark indicates additional support for that box's ideas.

1.4.2 Exemplar Partnerships

The climate vulnerability, resilience, and adaptive capacity communities within both the study region (the Baltimore metropolitan area) and the greater Chesapeake region are large and multifaceted. Since the effects of changing environmental conditions manifest in varied ways, suggestions for adaptation are equally varied and come from wide-ranging groups. Several federal entities aim to coordinate research and adaptation efforts, form collaborations across these groups, and help keep everyone up to date on new research and funding opportunities as they emerge. Notably, the Chesapeake Bay Agreement, which organizes state and federal cooperation for protection and restoration of the Bay, is due for renewal in 2025. Many planning activities are currently underway to address the Beyond 2025 report, which recommends that climate and social impacts across all existing priority areas should be added to the Bay Agreement (Beyond 2025 Steering Committee, 2024).

Ongoing larger-scale research efforts are discussed in section 1.4. Here, two community groups are highlighted as examples of organizations positioned to take information about vulnerability and apply it to adaptation and increasing resilience: NeighborSpace and the Evolve Community Foundation. These groups served as advisors to this work through regular consultations on preliminary results, orchestrating site visits to their community projects and facilitating introductions to other stakeholder groups.

1.4.2.1 NeighborSpace

NeighborSpace is a community land trust that operates between the city's jurisdictional boundaries and the edge of urban development in the region (the shape of which is featured in their logo, Figure 5). They serve a population often left out of city initiatives that faces common challenges associated with urban space, such as limited exposure to nature. They are part of a larger network of land trusts in the region, tailoring the strategies of their land trust to the needs of the neighborhoods they serve. According to their website, NeighborSpace serves an area where there is no green space available within a 5-minute walk for 65% of residents, most watersheds are impaired by sediment and/or nutrients, and the median home values lag behind other jurisdictions (NeighborSpace, 2025). In response, they manage 21 protected areas totaling 100 acres in area. These areas, while sometimes "pocket" sized, provide a multitude of ecosystem service benefits for nearby residents. Given the role urban development (i.e., impervious surface) has in increasing many components of vulnerability, green space protection can directly reduce vulnerability to climate hazards.



Figure 5. NeighborSpace logo, highlighting their service area of urban zones outside the city.

1.4.2.2 Evolve Community Foundation

The core of Evolve Community Foundation’s work is embodied in their “BEACH Life” program, which stands for business, education, arts, community, and health. Their programs, largely aimed at a youth audience, support all five pillars of their programming simultaneously and through connections to nature and by strengthening ties between existing institutions and community groups in Baltimore City. They have ties to Baltimore City Public Schools as well as Baltimore Parks and Recreation, both of which give them a physical footprint in the city to be able to provide after-school programs (see example facility in Figure 6). The Foundation’s work is critical in incorporating the effects of changing environmental conditions into community conversations, while also addressing more immediate community development.



Figure 6. Bilal “Coach” Bihar, leader of Evolve Community Foundation, leading a tour of one of their facilities in Baltimore County. Credit: Amy Freitag (NOAA NCCOS).

Part 2: Assessment Components

Assessment components are determined through indicator development and assessing vulnerability and hazards (steps 2 and 3 in Figure 1, respectively). Each component will be presented and visualized at the highest available resolution before integrative analysis, which occurs at the census block scale. For this assessment, five components of risk were assessed as prioritized by project partners and stakeholders: population projections, structural exposure, ecosystem service valuation, flooding hazard, and urban heat hazard (see Appendix A for definitions, Table 2 for a summary of the approach for each component, and Appendix C for data source references).

Flooding hazard is further divided into three sub-components: stormwater, storm surge, and sea level rise. Indicator data were collected for each at the highest spatial resolution possible and then aggregated to census block groups for comparison with each other, as population projection was the least spatially resolute component (at the block group scale). Depending on the spatial resolution and dynamics of each layer, results for each component will be depicted in maps of the entire study area or small-scale maps of key areas for each jurisdiction within the study area, as determined with project partners to balance data dynamics and stakeholder interest. Scales are depicted in continuous color ramps to avoid threshold effects. Error estimates and other metadata for each component can be found in the data archive:

<https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/HZDQEF>

Table 2. Summary of assessment components, analytical approach, and spatial resolution. MD DNR = Maryland Department of Natural Resources; MDL = Meteorological Development Laboratory; MCCC = Maryland Climate Change Commission; LULC = land use/land cover.

Component	Analytical Approach	Resolution
Population Projections	Data directly from Baltimore Metropolitan Council	Census block group
Structural Exposure	Index of 22 indicators (see section 2.2 for details)	Census block group
Ecosystem Service Valuation	Data directly from MD DNR	30 m × 30 m
Flooding Hazard – Stormwater	Index of 7 indicators (see section 2.4.1 for details)	30 m × 30 m
Flooding Hazard – Storm Surge	Data directly from NOAA MDL	Polygons of flood levels
Flooding Hazard – Sea Level Rise	Data directly from MCCC	Polygons of flood levels
Urban Heat	Index developed from Chesapeake Conservancy LULC (see section 2.5 for details)	1 m × 1 m

2.1 Population Projections

By 2050, population density is projected to increase across the study area, though disproportionately in different regions of the study area (Baltimore Metropolitan Council, 2024). Population is expected to grow in suburban and rural areas like Columbia and Maryland, as well as in the inner harbor of Baltimore City. Although the inner harbor is projected to grow, other Baltimore City neighborhoods are expected to decline as shown in Figures 7 and 8 (Baltimore Metropolitan Council, 2024). These contrasting population projections for Baltimore City have been attributed to ongoing gentrification outside of the inner harbor presently occurring due to an influx of middle-class or wealthy people into partially vacated neighborhoods (Brown et al., 2015; Richardson et al., 2019). Gentrification has already occurred in the inner harbor of Baltimore City with the revitalization of historic buildings and arrival of wealthier residents and is one reason why the inner harbor shows population growth instead of decline (Mallach, 2020).

Outside of Baltimore City, overall population trends in the study follow suburbanization patterns observed nationwide (Toukabri and Delbe, 2022). The Census Bureau attributes this recent pattern of population stability in cities and population growth in rural or suburban towns to the covid-19 pandemic and remote work policies. These allowed workers to no longer go into the office in person, and to move out of cities, away from their places of employment and into more affordable housing areas (Spell and Perry, 2024).

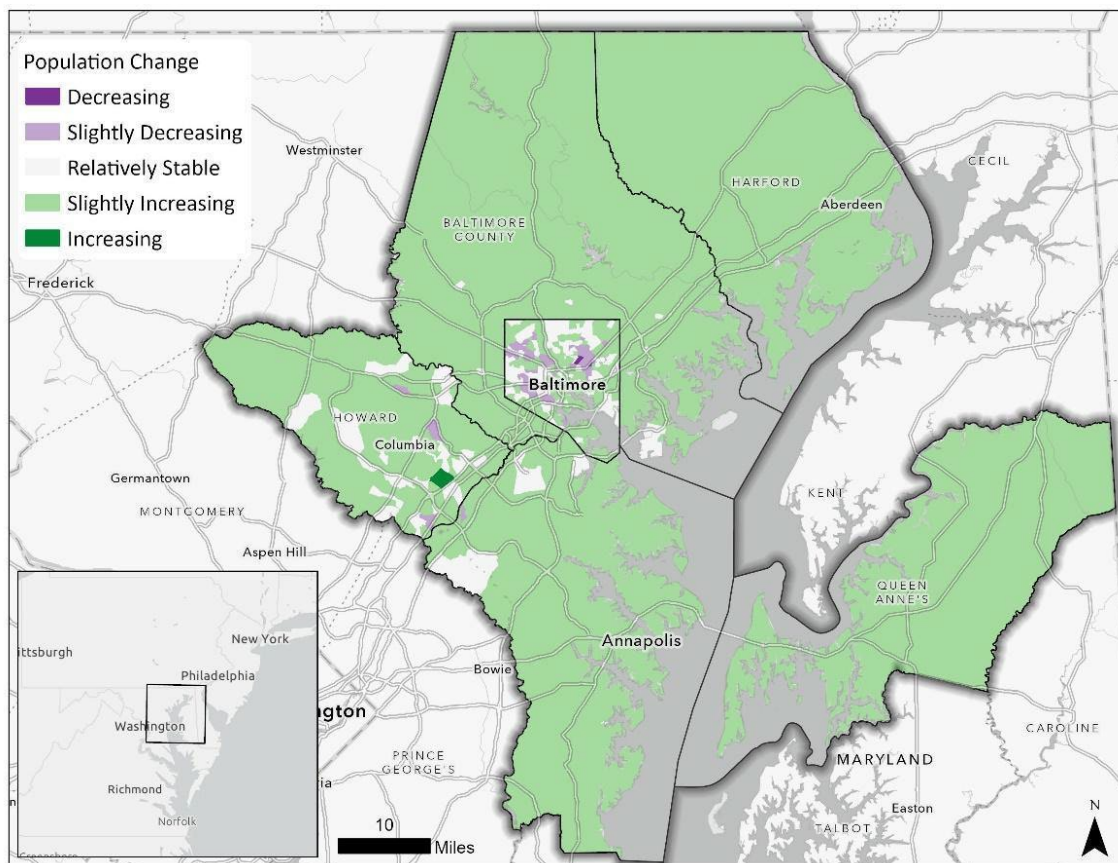


Figure 7. Population estimates using projection data from the Baltimore Metropolitan Council for 2050, with dark green showing increasing population and dark purple indicating decreasing population.

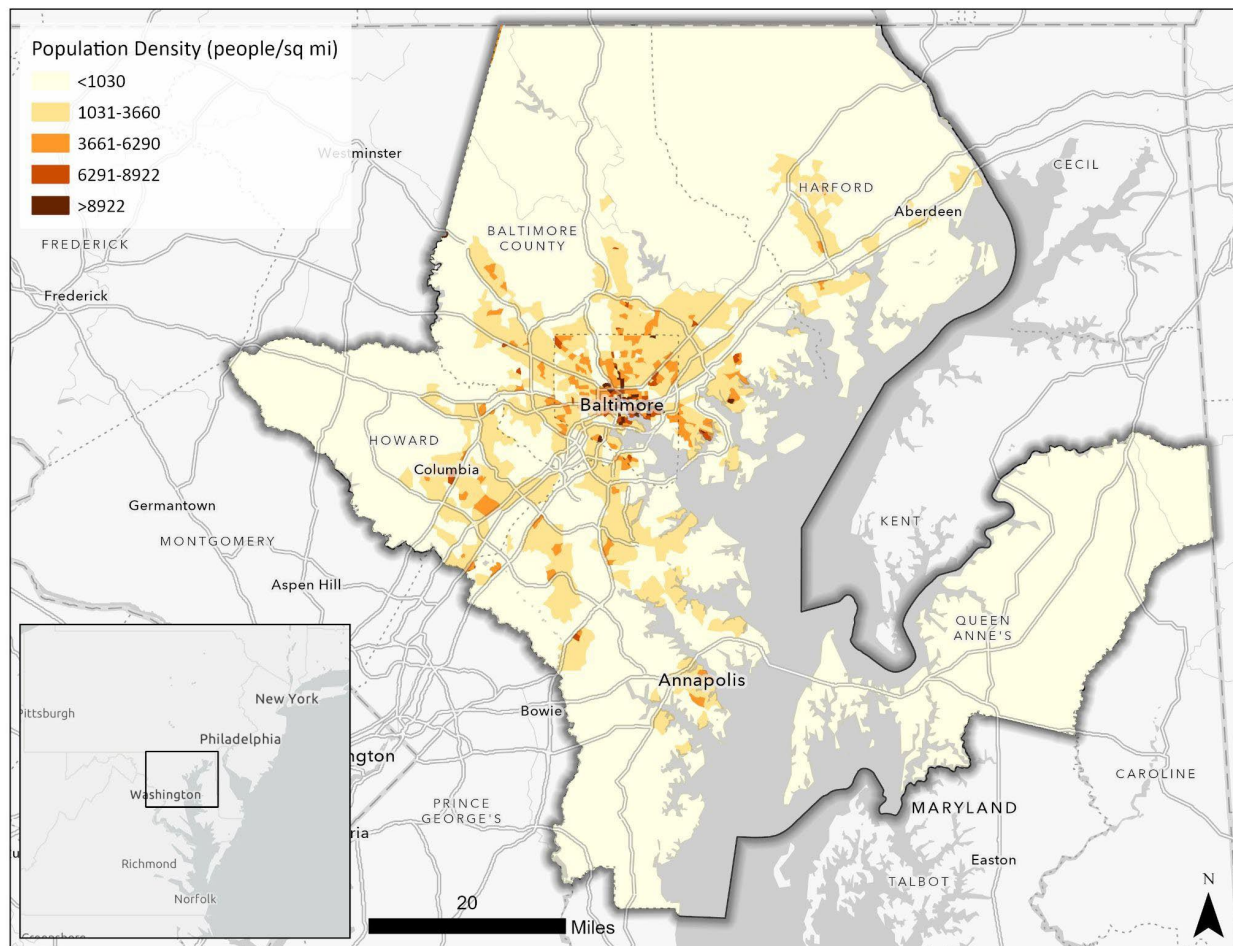


Figure 8. Population estimates using projection data from the Baltimore Metropolitan Council for 2050, with low population density in light yellow and high population density in dark red.

The Integrated Climate and Land-Use Scenarios (ICLUS) 2.1.1 population is a mathematical model developed by the Environmental Protection Agency (EPA) to project population and housing density in 2100 using fertility and mortality rates, migration trends, projected land use and land cover changes, climate scenarios ("GISS-E2-R" or "HadGEM2-ES") and economic scenarios (SSP2 and SSP5) (U.S. EPA Office of Research and Development, 2016). Projected population changes in the Baltimore Metropolitan Area are heavily reliant on these differing climatic and economic scenarios. If the economy continues to grow, with an increased reliance on fossil fuels and expansion of land development, under all climate conditions, population is projected to increase by approximately 60% in the study area (U.S. EPA Office of Research and Development, 2016). If the economy remains stable, the population is expected to remain relatively stable, decreasing by 5% if sea level rise is more severe, and increasing by 7.6% if there are less-severe winters due to changing environmental conditions. These projections are overarching for the area and do not take into account demographic shifts and smaller-scale population dynamics at the county, city, or town levels. In addition, these models were developed before the covid-19 pandemic and are not currently maintained as census data become available. However, they are the only projection data available that incorporate both land use and climate predictions and may still be useful to identify general trends.

Under the current baseline scenario (which assumes economic growth and demographic composition remain the same as today), population projections vary widely across the study area. Baltimore County and Queen Anne's County are expected to maintain relatively stable populations, while Anne Arundel and Hartford Counties are projected to experience moderate population growth, as shown in Figure 9 (U.S. EPA Office of Research and Development, 2016). The most substantial increase is anticipated in Howard County, with a projected 236% rise in population, focused on in Figure 10 with the more-detailed population projections from the Baltimore Metropolitan Council (2024). In contrast, Baltimore City is the only jurisdiction in the study area with a projected decline in population of approximately 12% (U.S. EPA Office of Research and Development, 2016). It is important to note that substantial changes in housing density, such as those projected for Howard County, may be limited by zoning ordinances, infrastructure capacity, and carrying capacity. These projections reflect current land use/land cover and demographic trends.

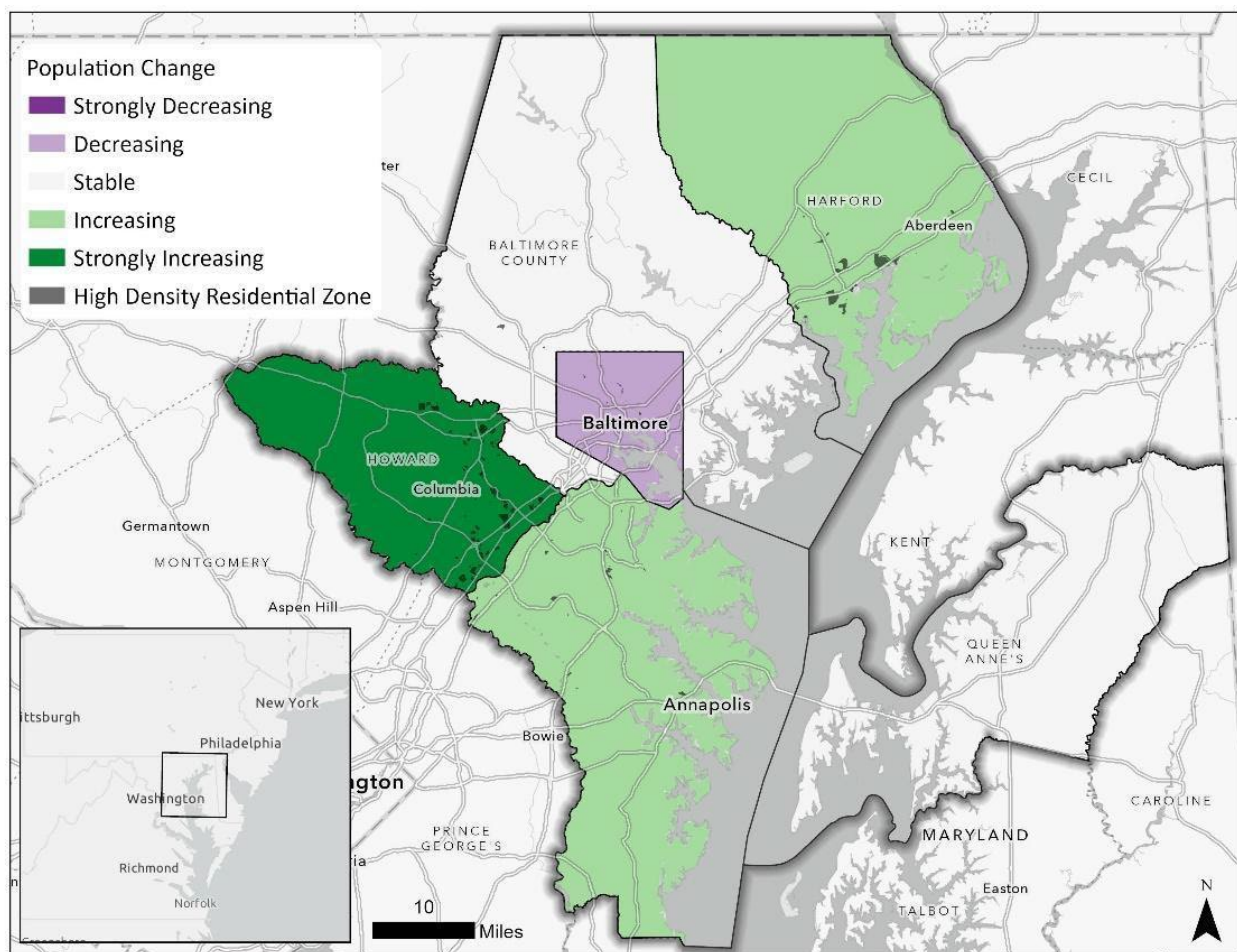


Figure 9. County-wide population increase, with high density residential zoning overlaid.

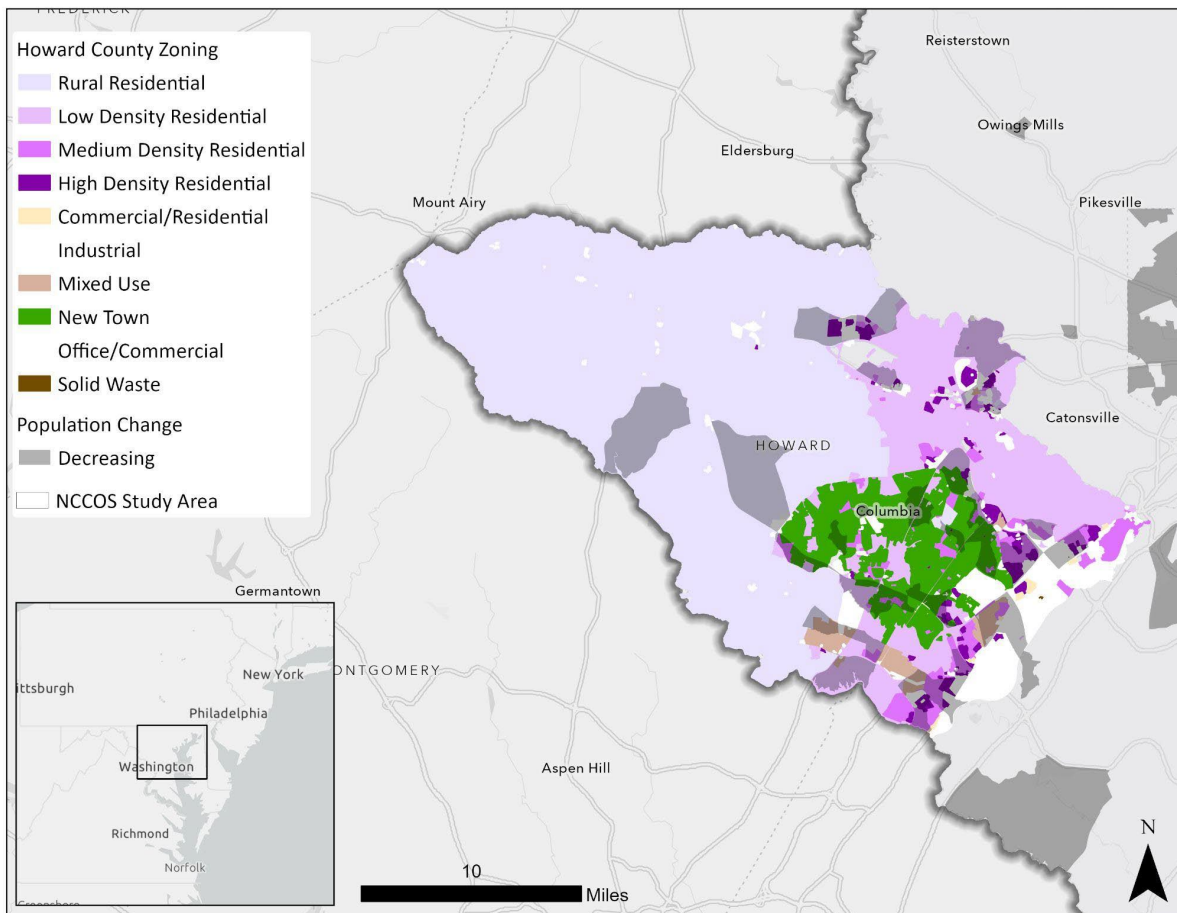


Figure 10. Howard County, an area with high projected population increase, with zoning overlaid. Block groups with expected population decrease areas in the Baltimore Metropolitan Council 2024 projections are masked in gray; everywhere else is expected to increase to some degree.

2.2 Structural Exposure

Structural exposure highlights locations of many types of critical infrastructure; an Index is created to incorporate all regional infrastructure concerns. While there is no standard index for structural exposure, Baltimore City began accounting for structural exposure in its hazard mitigation plan, which included a self-assessment of critical facilities at risk of impacts from changing environmental conditions (City of Baltimore, 2013). This self-assessment was completed in 2013 and focused on Baltimore City; as a result, the structural index presented here compiles the desired indicators from that self-assessment and adds considerations from the project scoping process, including places of worship, farms, shoreline infrastructure, and stormwater infrastructure (Table 3). In addition, gas stations were combined with electric-vehicle charging stations, and public transit lines were added to represent all modes of transit. The Baltimore self-assessment also identified a few categories that this study folded into another category: Water pumps were included in drinking water infrastructure since most of the datasets combined them (excluding private wells), and sewage facilities were included in wastewater treatment plants since the vast majority are city plants (excluding private septic systems). Private wells and septic systems remain

vulnerable around the Bay. To address this, the Chesapeake Bay Restoration Fund provides resources to transition to city water systems (Maryland Code Ann., Environment, 2004); however, data on privately held operations is not currently available.

Table 3. Indicators included in the structural exposure index and their origin.

Indicator	Origin
Banks	Baltimore self-assessment
Bay access points	Project scoping
Colleges	Baltimore self-assessment
Critical roadways	Baltimore self-assessment
Drinking water infrastructure	Baltimore self-assessment
Electricity production	Baltimore self-assessment
Emergency shelters	Project scoping
Farms	Project scoping
Fire stations	Baltimore self-assessment
Gas stations + electric vehicle charging	Baltimore self-assessments (with update)
Government facilities	Baltimore self-assessment
Grocery stores	Baltimore self-assessment
Hardware stores	Baltimore self-assessment
Hazardous waste facilities	Baltimore self-assessment
Hospitals	Baltimore self-assessment
Places of worship	Project scoping
Police stations	Baltimore self-assessment
Public transit lines	Supplement to Baltimore self-assessment
Schools	Baltimore self-assessment
Shoreline protection	Project scoping
Stormwater infrastructure	Baltimore self-assessment
Wastewater infrastructure	Baltimore self-assessment

Stormwater infrastructure data are held by each county or city and available by request of the public works department of each jurisdiction. Therefore, the stormwater data are not included in the final geodatabase for this assessment but are included in the analytics and maps reported here. To access these data, refer to the data inventory and relevant contacts for stormwater infrastructure data. In addition, due to differences in data availability across the jurisdictions, this analysis focuses on outfalls and stormwater piping only. In some areas, more detailed engineering data are available for inputs into hydrodynamic models, such as the EPA's Stormwater Management Model (see section 1.4.2 for more detail on ongoing work on this topic).

Final data sources included the Department of Homeland Security's Homeland Infrastructure Field-Level Data, Maryland's iMap geospatial database, and ESRI's business analyst (see Appendix C for more details). A total structural exposure index was developed by aggregating each contributing indicator to the block group by using the Summarize Within tool in ArcGIS Pro 3.4, yielding a count of total sites or total meters of infrastructure (for roads and pipes) for each block group. Each of the 22 contributing indicators was min-max normalized to a 0–1 scale, and these normalized values were summed to produce a composite structural exposure index ranging from 0 to 22 for each block group. Results are displayed per area of the block group (Figure 11); most critical infrastructure is located in downtown areas and along major highways (highlighted areas in Figure 12).

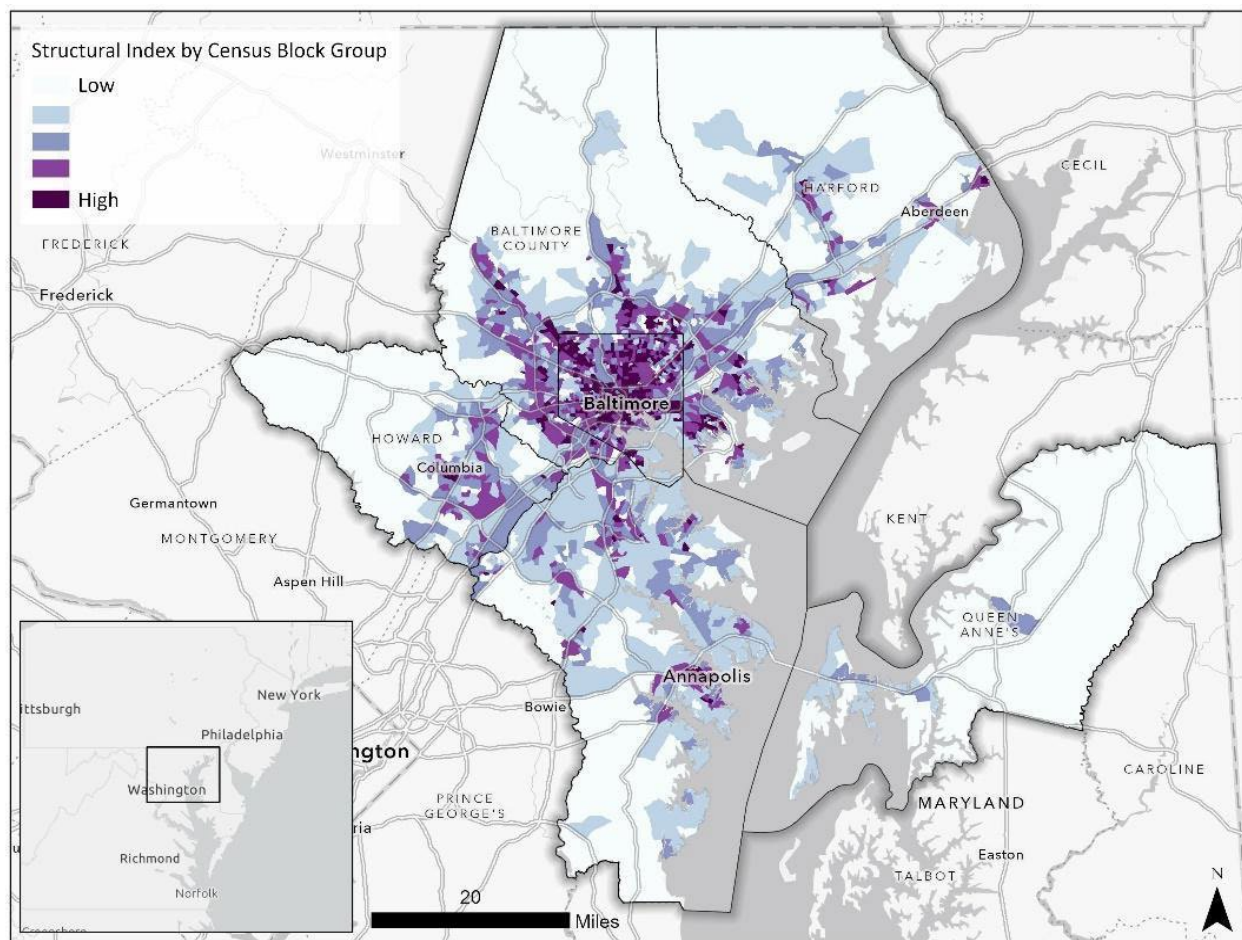


Figure 11. Structural Exposure Index per block group, normalized by area of the block group.

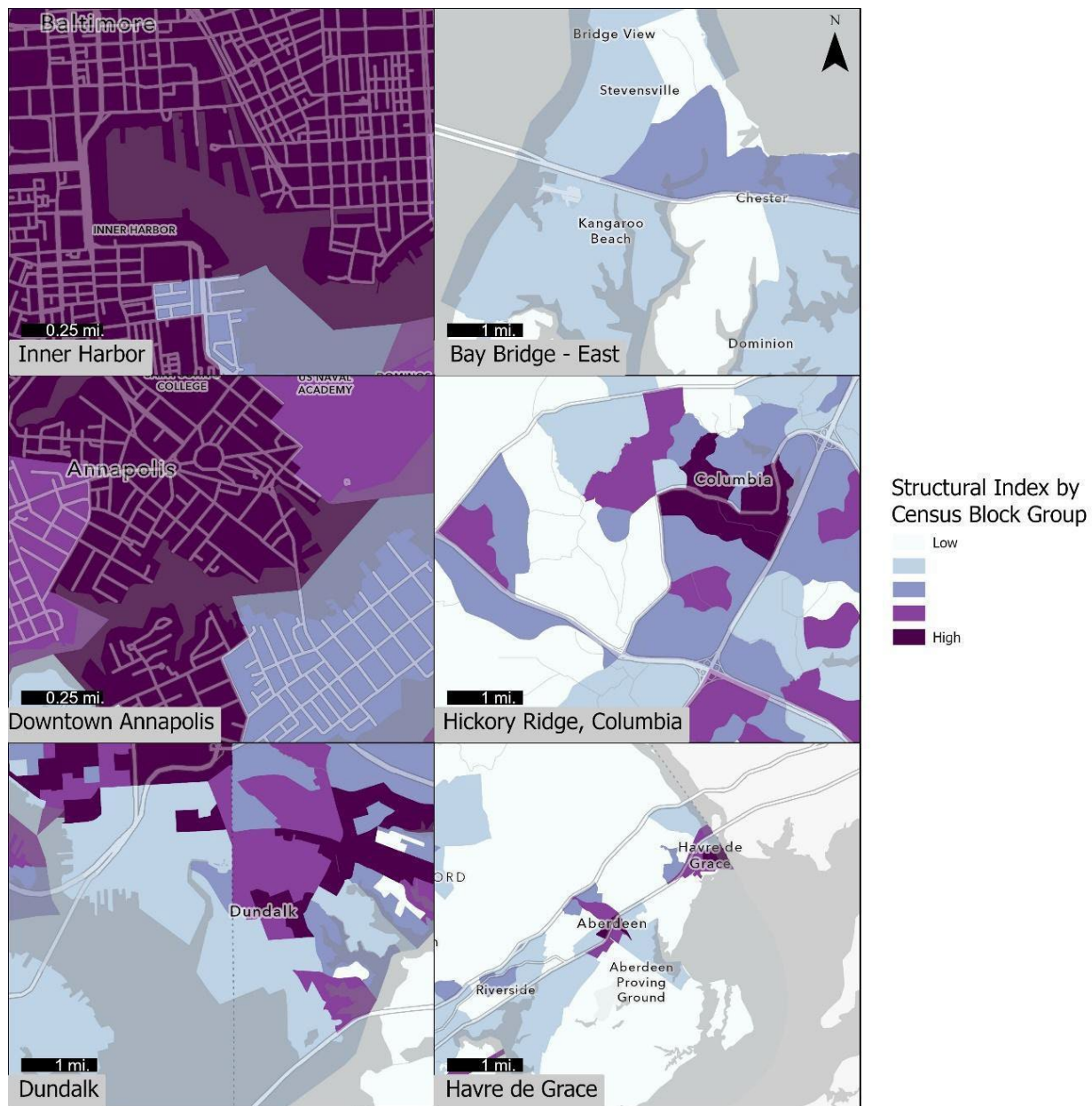


Figure 12. Structural Exposure Index per block group area shown for highlighted neighborhoods.

2.3 Ecosystem Service Value

The complex Chesapeake habitats in the study region provide a wide range of ecosystem services—benefits people receive from natural ecosystems, such as clean air, water filtration, flood protection, and wildlife habitat. These would be costly or impossible to replace if the ecosystem is degraded (Campbell et al. 2017). To assess the economic importance of these services, the Maryland Department of Natural Resources has developed a high-resolution Return on Environment model, which estimates the dollar value of ecosystem services across the state. These values are intended to quantify the public benefits provided by natural

systems, not to reflect market prices or facilitate market transactions. Rather, the estimates were designed to support decision-making around compensatory impacts on state-owned lands (Campbell et al., 2017).

The analysis focuses on seven key ecosystem services: a) atmospheric pollution removal, b) carbon sequestration, c) groundwater recharge, d) nitrogen removal, e) flood prevention and stormwater mitigation, f) wildlife habitat and biodiversity, and g) surface water protection (Campbell et al., 2017). While these represent only a portion of the services provided by the Chesapeake Bay ecosystem, they emphasize regulating and supporting services that control natural processes and maintain ecological functions, because they can be quantified economically. These services form the foundation that enables provisioning and cultural services. In this way, the selected services are essential precursors to the broader benefits the ecosystem provides (Freitag et al., 2018).

The total estimated value of these ecosystem services, modeled by Campbell et al. (2017), is shown in Figure 13, aggregated by census block group as the average value of the raster pixels within each block group. Darker green shades indicate higher average values, while lighter shades and white represent lower values, ranging from \$2.40 to \$669 per pixel (2016 dollars). The highest service values are concentrated in the more rural portions of the study area. Figure 14 presents the original, higher-resolution data in highlighted areas.

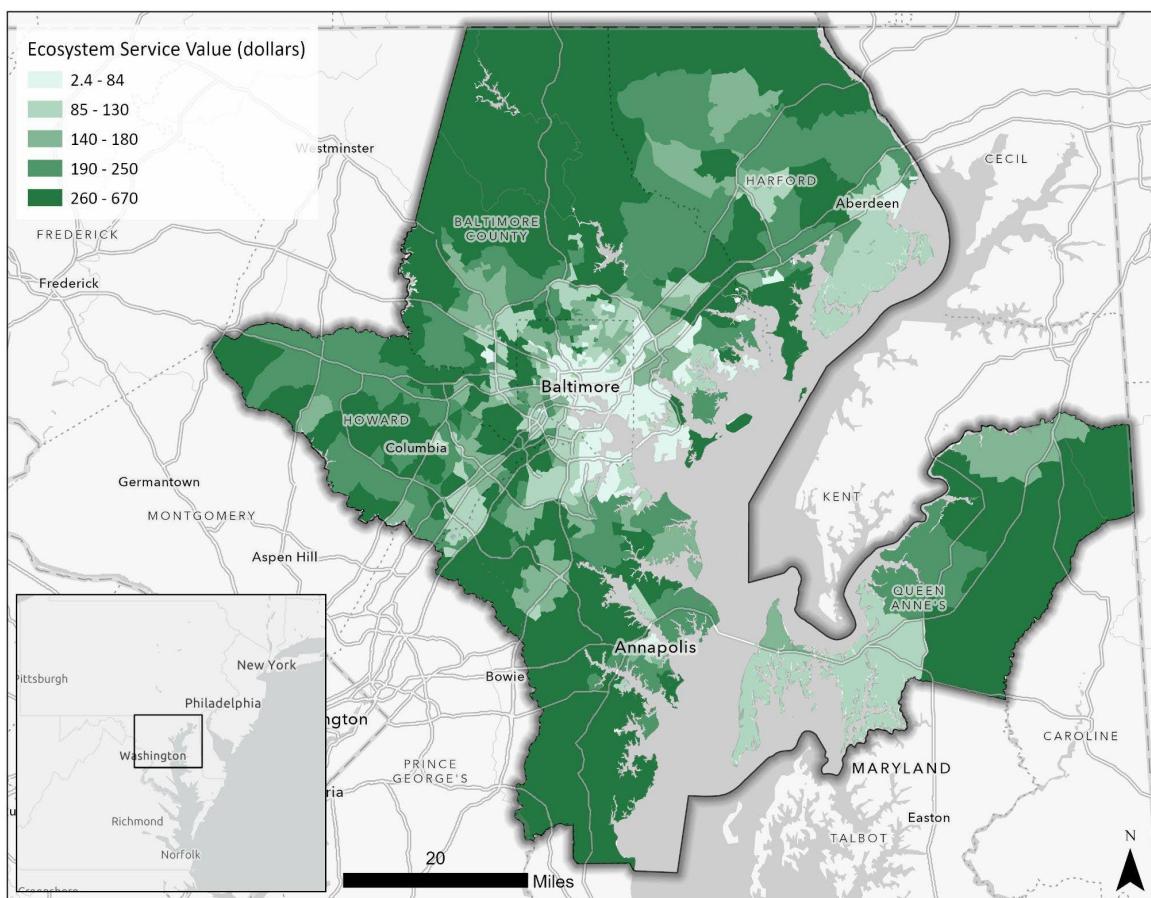


Figure 13. Average ecosystem service value by block group.



Figure 14. Total ecosystem service value (in dollars) for the highlighted areas, showing the original data at a 30-m by 30-m resolution.

2.4 Flooding: Stormwater, Sea Level Rise, Storm Surge, and Compounded

2.4.1 Stormwater Flooding

Flooding hazards represent a persistent and significant threat, particularly in areas prone to extreme weather events or with inadequate drainage systems. Hazard likelihood can stem from natural topography, proximity to water bodies, structural design flaws, or the prevalence of impervious surfaces. Stormwater flooding in particular is a pressing issue in the Baltimore Metropolitan Area, showing substantial variability across the region (Miro and Grocholski, 2023). However, data on stormwater flooding risks for the broader five-county region remain limited. While some stormwater flooding models exist within the city of Baltimore (Javier et al., 2007) and select regional climate analyses have been conducted for the larger Chesapeake region (Miro and Grocholski, 2023), comprehensive assessments at the regional scale are scarce, particularly for stormwater-driven flooding.

To address this gap, the assessment team developed a precipitation-driven stormwater flooding hazard layer for the study area. This analysis utilized the FIGUSED methodology, introduced by Kazakis et al. (2015), implemented in ArcGIS Pro 3.4 to identify areas with high flood potential. This methodology uses equal weights for all indicators. Kazakis et al. (2015) performed a sensitivity analysis as part of their original model development. After consultation with Maryland Department of the Environment stormwater engineers, the model was implemented as originally constructed without local adaptations such as indicator weightings. Future research to validate indicator weightings is desired but requires primary data collection and was beyond the scope of this study. The following sections detail each of the seven components of the FIGUSED model:

FIGUSED Index Value = Flow Accumulation + Rainfall Intensity + Geology + Land Use + Slope + Elevation + Distance from Drainage

2.4.1.1 Flow Accumulation (*F*)

Flow accumulation refers to the amount of surface runoff collected in a specific area. This quantitative measure is critical for delineating drainage zones. According to Jenson and Domingue (1988), flow accumulation is calculated using a digital elevation model (DEM). For the study area, a flow accumulation raster was calculated based upon a 30 × 30 m DEM from the U.S. Geological Survey (USGS) (2024a). Flow direction was calculated first by interpolating missing connections in the data (filling sinks), then calculating flow direction, and finally calculating a flow accumulation value for each raster pixel based on the number of upstream cells that flow into it (Figure 15).

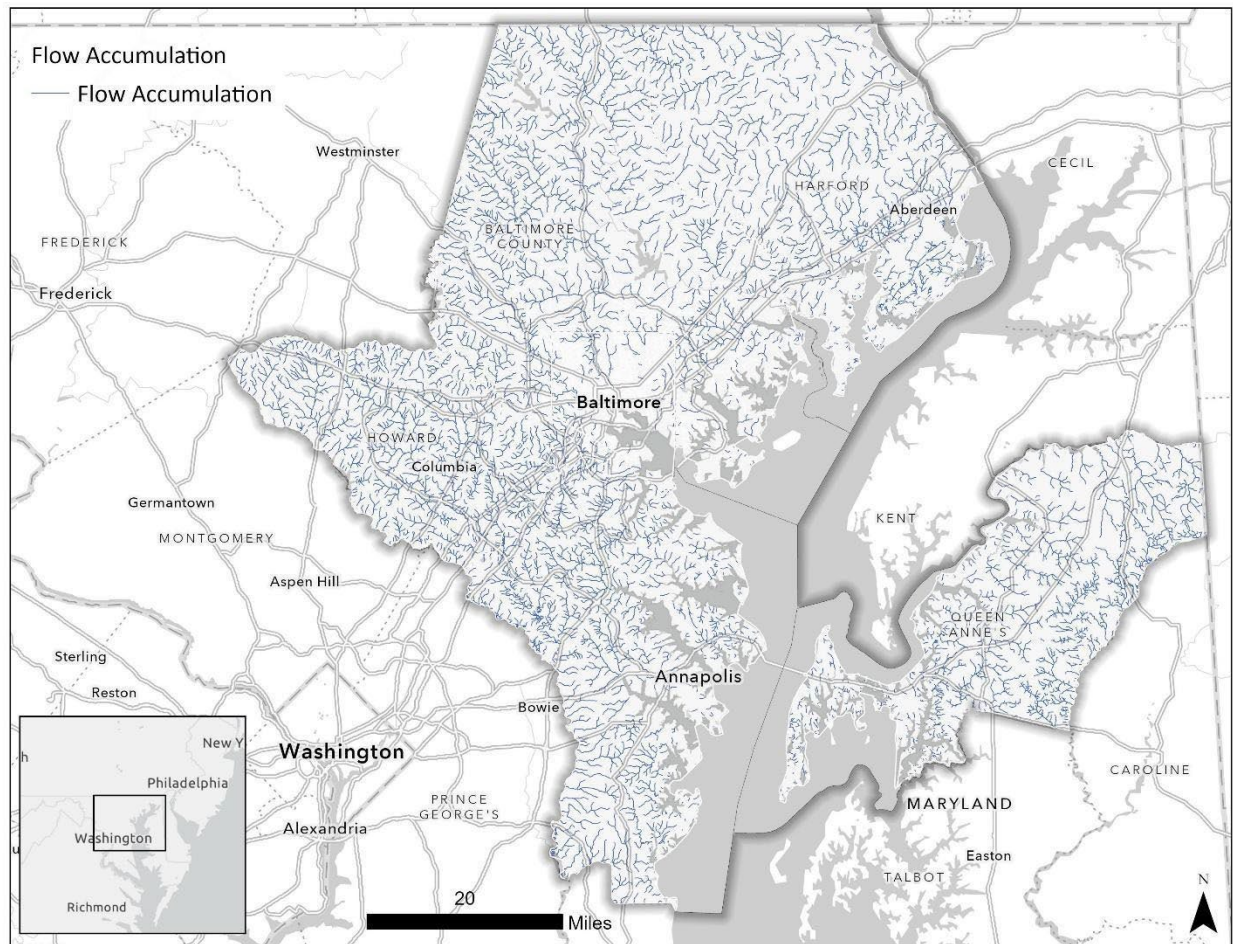


Figure 15. DEM-derived flow accumulation for the study area.

2.4.1.2 Rainfall Intensity (I)

Rainfall intensity is a critical factor in assessing flood risk as it determines the rate at which water accumulates on the surface during precipitation events. High-intensity rainfall often leads to increased runoff, overwhelming drainage systems and increasing flood potential (Lin et al., 2022). In this study, rainfall intensity data were sourced from the National Oceanic and Atmospheric Administration (NOAA) and synthesized by the PRISM Climate Group (n.d.). The data consist of 30-year "normals" datasets averaged over the period from 1991 to 2020. These data provide spatially gridded average annual precipitation values at an 800-m resolution, offering a snapshot of current climate conditions and the overall chance of precipitation based on historical patterns. These data were rescaled to a 30×30 m grid to match the spatial scale of the DEM (Figure 16).

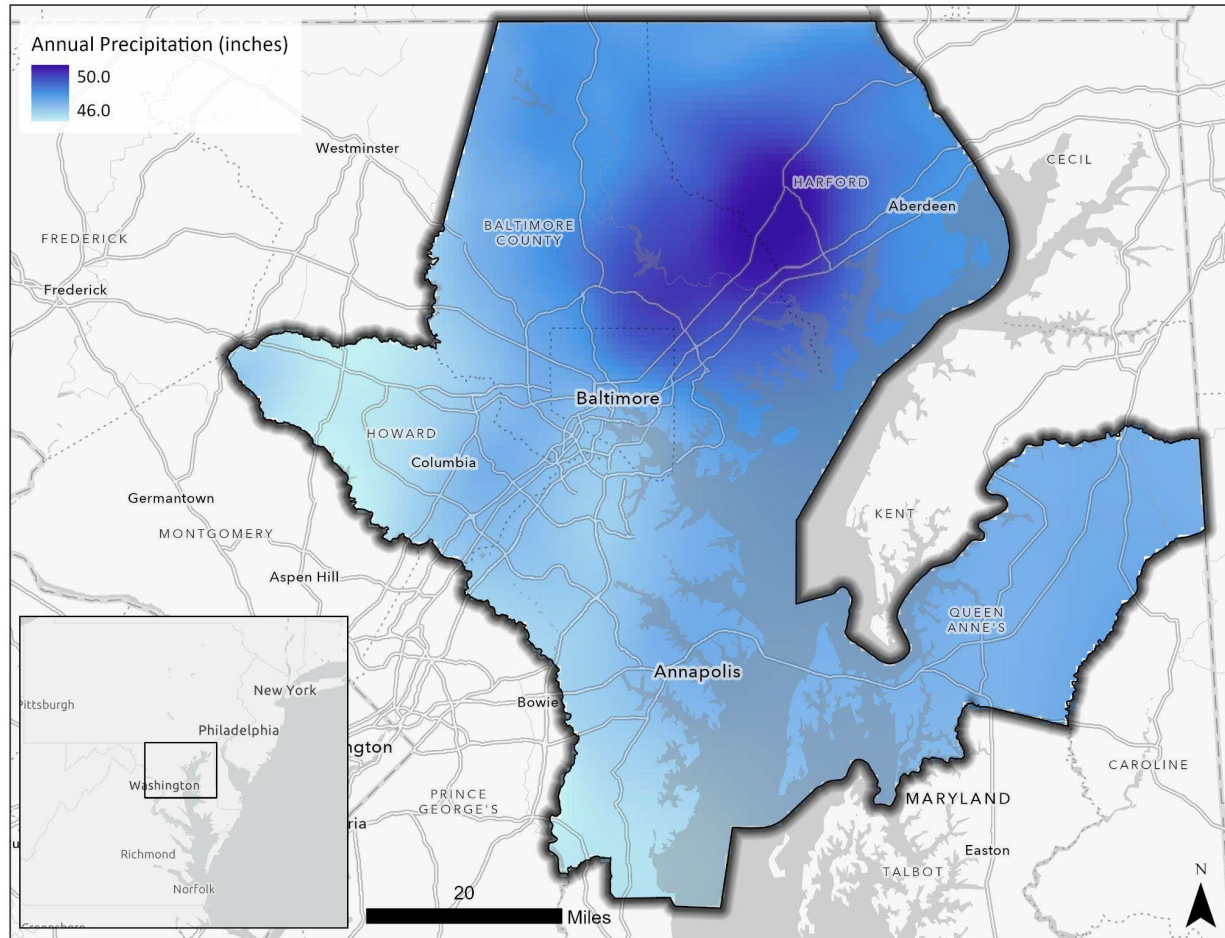


Figure 16. Average annual rainfall for the study area.

2.4.1.3 Geology: Hydrologic Soil Groups (G)

Soil type, mineral content, and permeability, as well as other characteristics, significantly influence runoff potential. Soil runoff potential is a process that includes the likelihood for surface runoff to occur during rainfall or precipitation. Surface runoff is generated when the movement of water into the soil is too slow to prevent all moisture being absorbed and thus allows water to flow along the land surface and downhill into sinks and other water sources (Phi et al., 2013). Certain types of soils are more prone to water retention and flood risk (National Resources Conservation Service Soil Survey Staff, 2023; U.S. EPA, 2022). The U.S. Department of Agriculture (USDA) soil survey (National Resources Conservation Service Soil Survey Staff, 2023) classifies soil types and potential runoff values into hydrologic soil groups. For this analysis in the Baltimore region, soil data from the Web Soil Survey were used to assign values to different soil groups in a 30×30 m raster. Consistent with the original FIGUSED methodology, survey areas categorized under hydrologic groups A and B (indicating well-drained or more absorbent soils) were assigned a value of 0, while areas falling into groups C, D, A/D, B/D, or C/D were given a value of 1, indicating a higher flood potential (Figure 17).

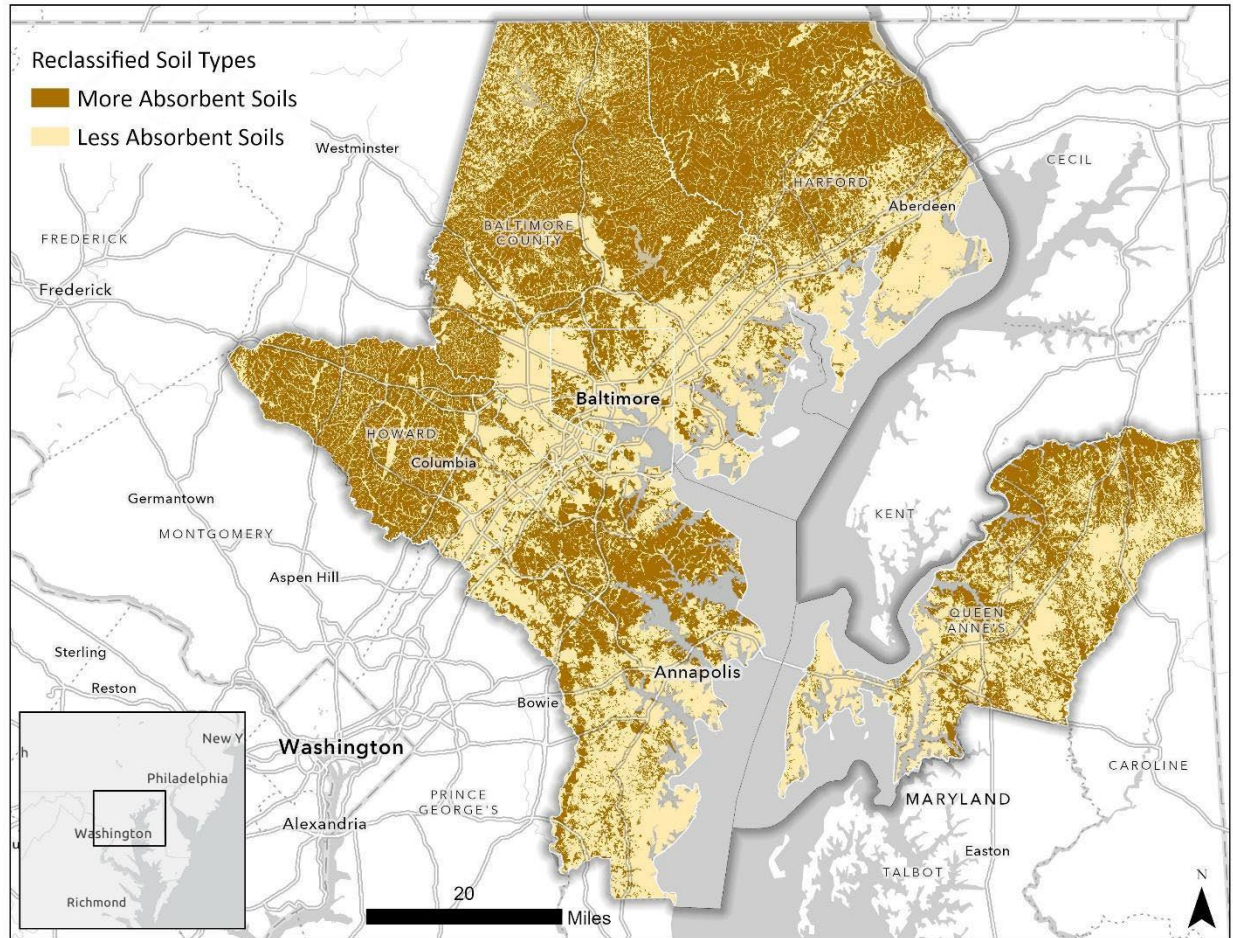


Figure 17. Soil types for the study area reclassified by the FIGUSED methodology; dark brown areas depict more-absorbent soils less prone to accumulating standing water (soil classifications come from the USDA National Resources Conservation Service Soil Survey Staff [2023]).

2.4.1.4 Land Use (U)

Land use and cover types play an essential role in determining flood risk, as different surfaces exhibit varying degrees of permeability and water retention. Areas characterized by impervious surfaces, such as urbanized zones, are more susceptible to surface runoff, while vegetated or forested regions tend to absorb and retain more water, reducing flood potential (Shuster et al., 2005).

Data for land use classification were obtained from high-resolution land cover datasets developed by the Chesapeake Conservancy in collaboration with the USGS and the University of Vermont Spatial Analysis Lab (Chesapeake Conservancy et al., 2022). The data cover the Chesapeake Bay watershed area and provide detailed information at a 1-m resolution. This classification helps to quantify the impact of land use on flood risk across diverse landscapes. The original land use classifications from the Chesapeake Conservancy data were reclassified as shown in Table 4.

Table 4. Reclassification values to convert land use/land cover data into flood risk values for FIGUSED.

Data Type	Reclassification Value
Water; Impervious Structures	10
Emergent Wetlands; Tree Canopy Over Structures; Tree Canopy Over Other Impervious; Tree Canopy Over Impervious Roads	8
Barren	6
Low Vegetation	4
Tree Canopy; Scrub/Shrub	2
Aberdeen Proving Ground	NO DATA

Land use data were then rescaled to match the spatial resolution of the 30×30 m DEM, and land cover types were min-max normalized on a scale of 0 to 1, with higher values assigned to areas more prone to flooding, such as wetlands (which flood as part of their ecosystem dynamics) or impervious surfaces (which flood because they are nonabsorptive) (Figure 18).



Credit: Amy Freitag (NOAA NCCOS)

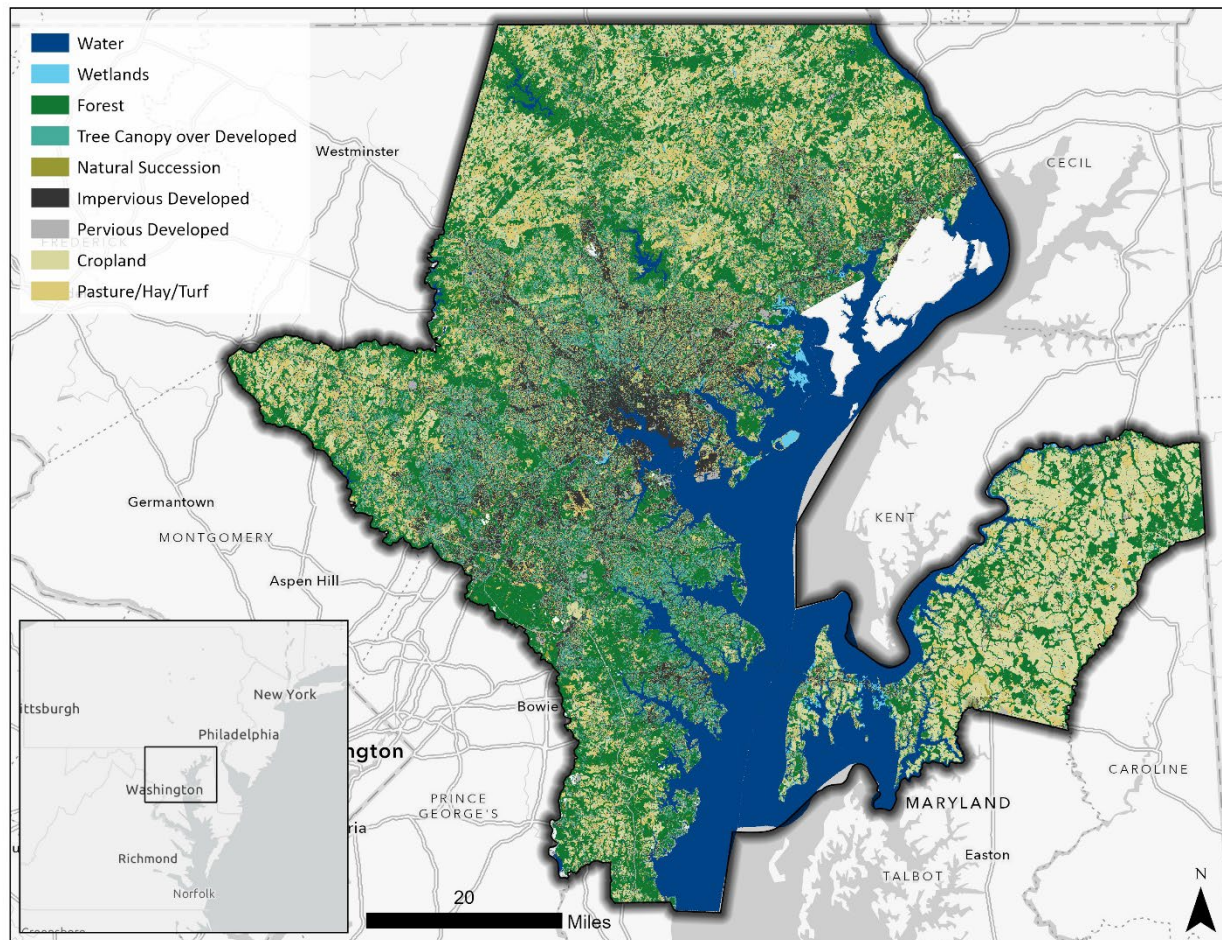


Figure 18. Land use/land cover for the study area depicted in 1×1 m resolution.

2.4.1.5 Slope (S) and Elevation (E)

Slope and elevation are intrinsic topographic features that influence surface water flow and runoff dynamics. Steeper slopes generally result in faster runoff and reduced infiltration, while flatter areas allow for water accumulation and increased flood potential. In the FIGUSED methodology, slope (Figure 19) and elevation data (Figure 20) were derived from DEMs, with values normalized from 0 to 1 to reflect their relative contributions to flood risk in the study area. Areas with lower elevation and gentler slopes were assigned higher values, indicating a greater likelihood of water accumulation and flooding, particularly during heavy rainfall events.

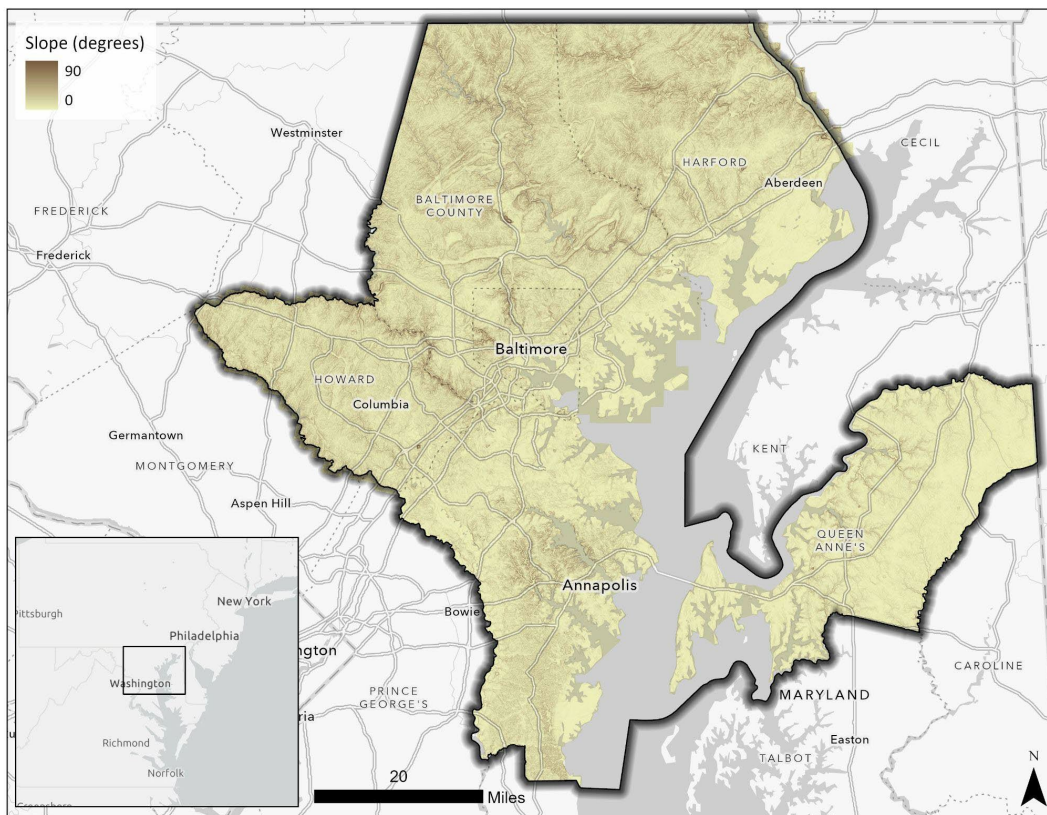


Figure 19. Slope across the study area.

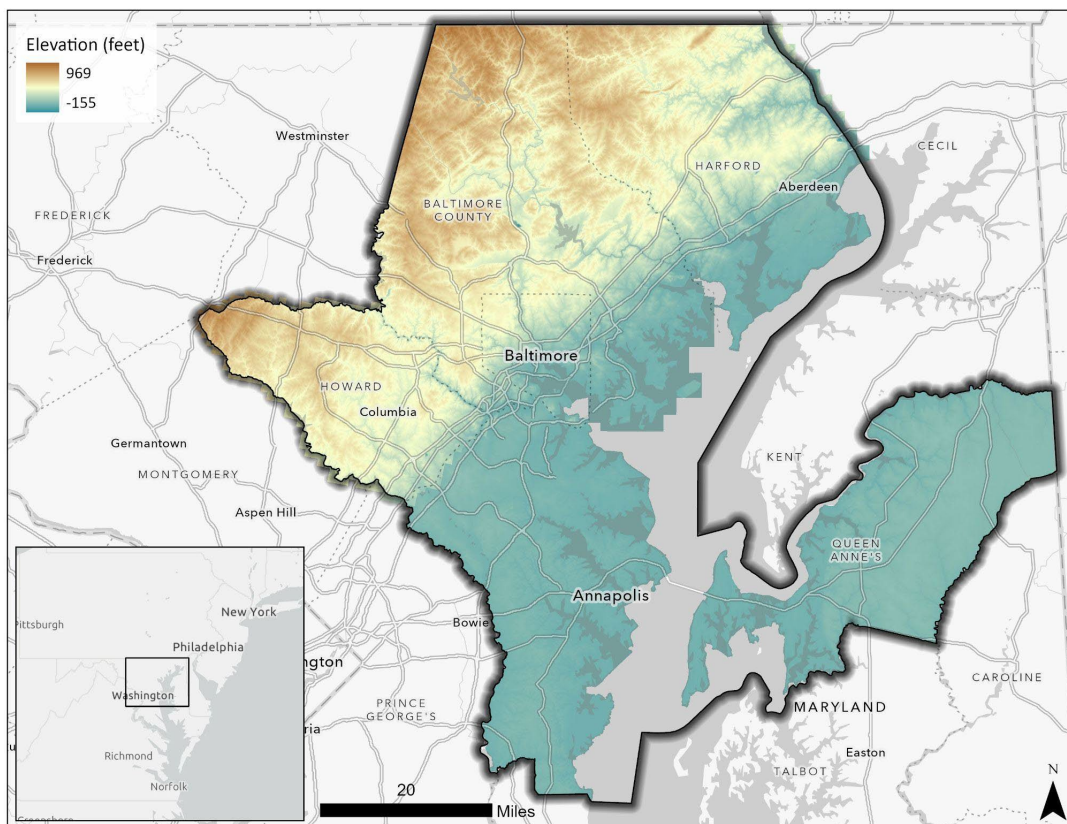


Figure 20. Elevation across the study area.

2.4.1.6 Distance from the Drainage Network (D)

The proximity of an area to natural drainage networks, such as rivers, streams, or other bodies of water, is a crucial determinant of flood risk. Regions that are situated closer to drainage sources are more susceptible to flooding due to their direct exposure to surface water flow during storm events. To capture this variable, a drainage network density grid was created using flowline data from the National Hydrology Dataset (USGS, 2020). The resulting 30×30 m grid was normalized between 0 and 1, with higher values indicating areas with a higher density of drainage sources (Figure 21).

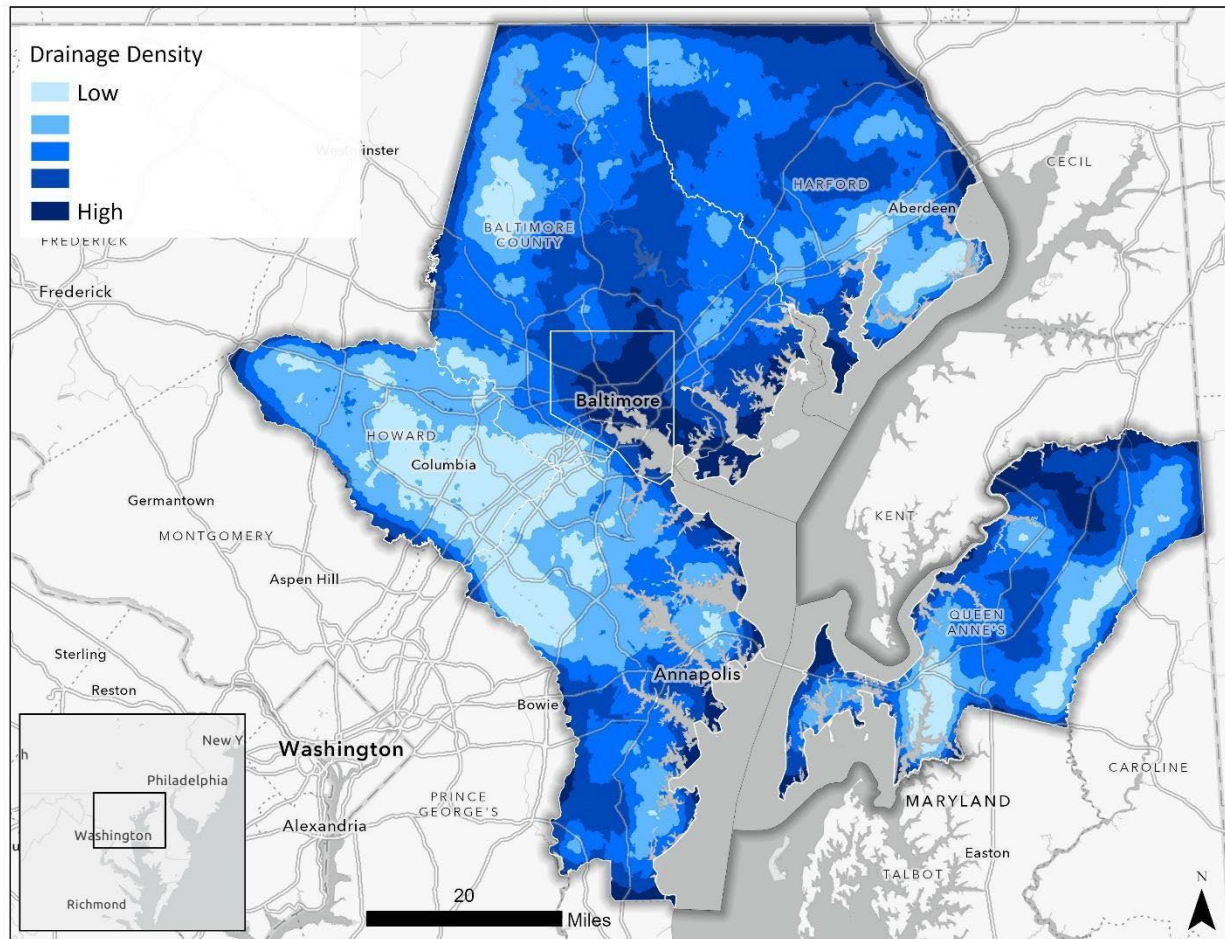


Figure 21. Distance from drainage network.

2.4.1.7 Integrating the FIGUSED Indicators into a Stormwater Flooding Hazard Index

Each of the seven FIGUSED indicators (Flow Accumulation, Rainfall Intensity, Geology, Land Use, Slope, Elevation, and Distance from Drainage) were integrated into a GIS framework, and an additive index was calculated at the 30×30 m grid resolution (Figure 22 for the study area; and Figure 23 for highlighted areas). This index creation inherently weights all the layers equally, but further context-specific data might warrant different weighting in future studies. The final stormwater flooding hazard index values range from

0 at the lowest possible value to a potential of 7, with higher values indicating a greater likelihood of stormwater flooding. The index values were then aggregated to census block groups, providing a comprehensive assessment of flood risk across the study area for comparison to population-based data (Figure 24). By incorporating these multifaceted environmental factors, the FIGUSED methodology provides a robust tool for flood hazard assessment, supporting more effective land use planning and disaster preparedness strategies in vulnerable regions.

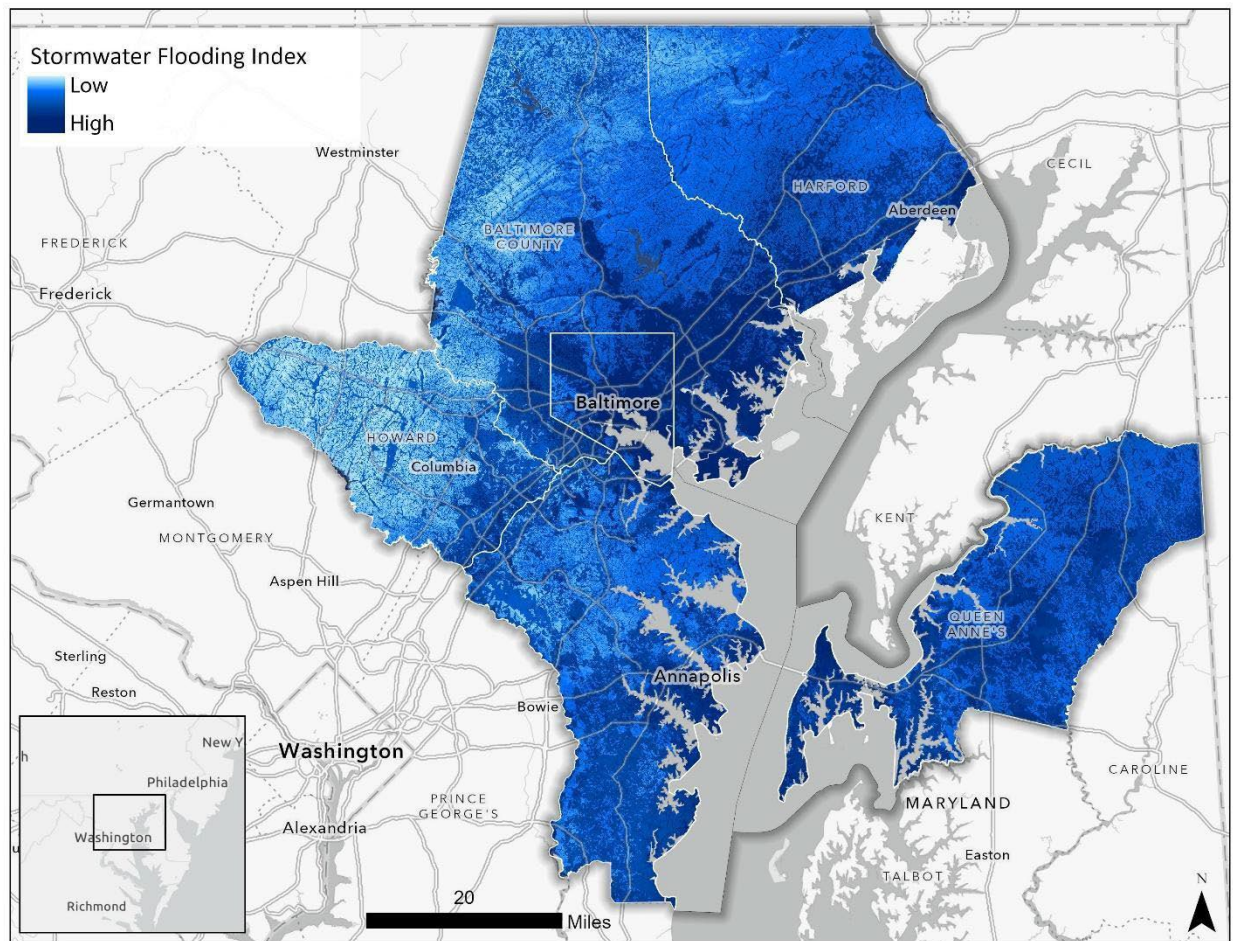


Figure 22. Final stormwater flooding index across the study area, shown at a 30 × 30 m resolution.

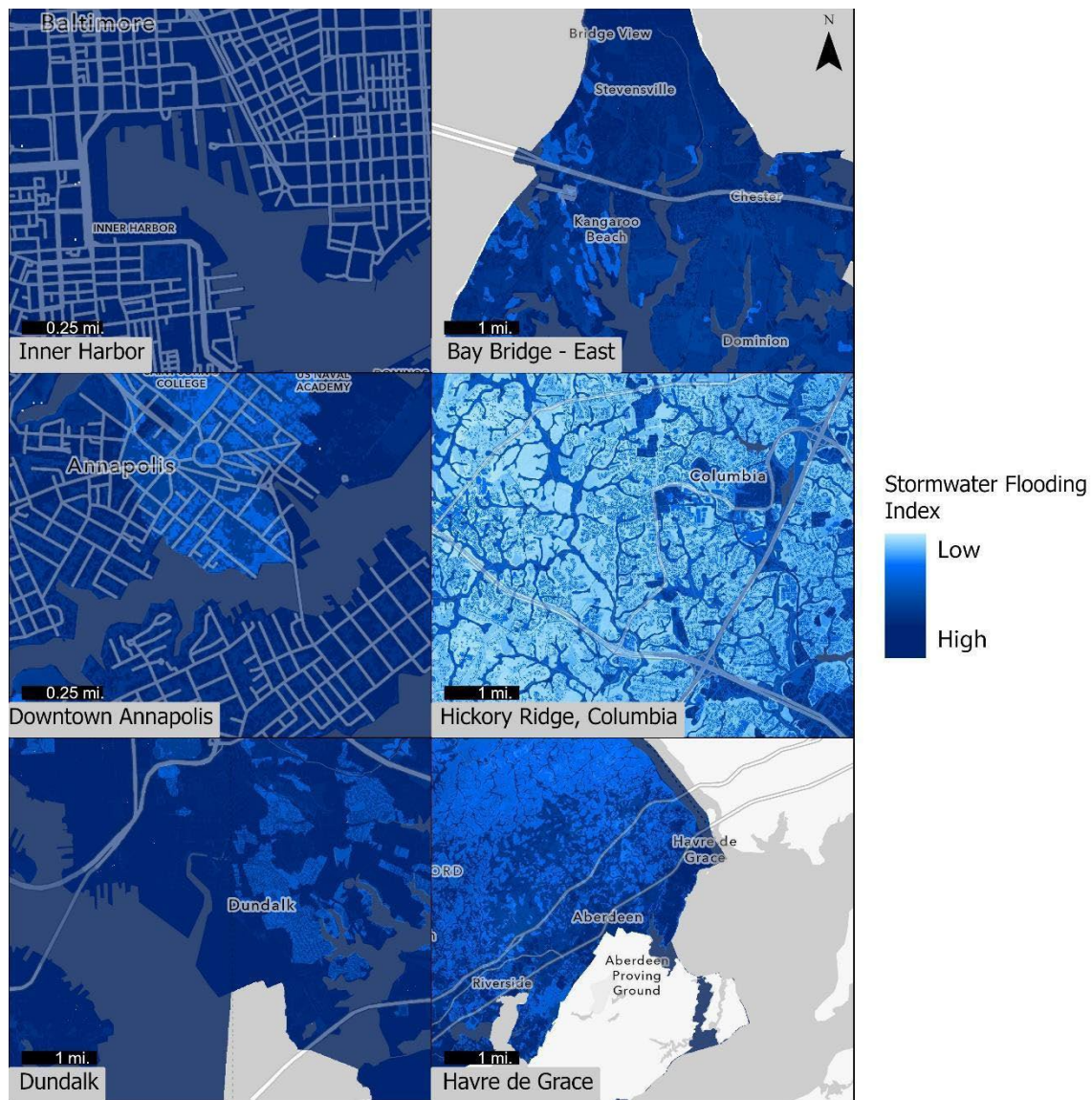


Figure 23. Stormwater flooding index for the highlighted areas. Darker blue indicates higher stormwater potential. High-resolution FIGUSED data shown for neighborhood detail.

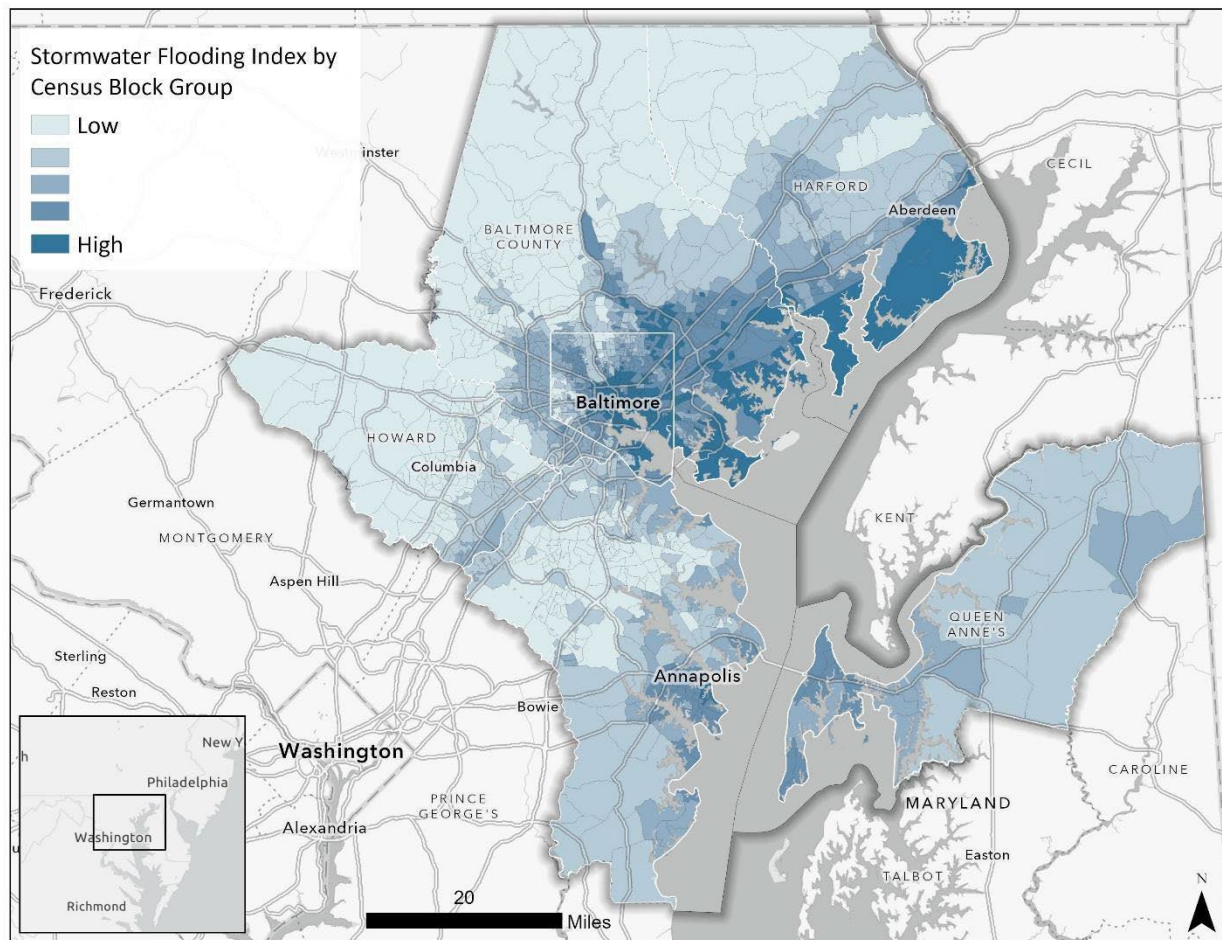


Figure 24. Mean value of stormwater flooding index for each block group across the study area.



Stormwater-related data represent a significant area of need, both in terms of high-resolution rainfall projections and stormwater infrastructure. Regarding resolution, the stormwater model used in this assessment integrates data layers ranging from 1 to 30 m, with the exception of rainfall intensity, which relies on coarser 800-m Weather Service grid data. Access to finer-resolution rainfall data would enable the model to operate entirely at 30-m resolution, aligning with other high-resolution datasets for the Chesapeake region.

The stormwater model applied reflects the best option available given current data limitations. However, more advanced stormwater analytics could be achieved with improved data on additional hydrological factors, such as dam-regulated flow rates, soil erosion potential, and stormwater piping capacity. Compounding this challenge, stormwater infrastructure data are currently collected separately by individual county or city jurisdictions, using inconsistent formats and standards. Harmonizing these data across the watershed(s) would enhance the potential for more detailed stormwater analyses, including the development of fine-scale hydrodynamic models similar to those produced for key neighborhoods (Shi et al., 2021) and ongoing efforts within the Baltimore Social-Ecological Collaborative.

2.4.2 Sea Level Rise

Sea level rise is a pressing issue along the Maryland coastline, and as a result, it is fairly well studied and reported on in the region. Organizations including the University of Maryland Center for Environmental Science, Maryland Commission on Climate Change, Maryland Sea Grant, Maryland Department of Natural Resources, NOAA, National Aeronautics and Space Administration (NASA), and USGS have conducted previous research and posted reports and tools on sea level rise in Maryland and the Mid-Atlantic region (Boesch et al., 2023; Cronin, 2013; Dahl et al., 2017; Strain et al., 2014). The Maryland General Assembly tasked the University of Maryland Center for Environmental Science with re-evaluating sea level rise projections every 5 years based on Intergovernmental Panel on Climate Change scenarios for changing environmental conditions (Boesch et al., 2023).

Sea level rise inundation does not necessarily convert the land directly to the Bay. Over the last 40 years, approximately 30,000 acres of forestland and farmland have converted to tidal marshland due to sea level rise (Boesch et al., 2023). Projections for 2050 estimate that an additional 150,000 acres of land could transition in this way, resulting in the loss of valuable ecosystem services traditionally provided by forests and agricultural lands (Boesch et al., 2023) and carry economic and ecological tradeoffs (Epanchin-Niell et al., 2017; Anthoff et al., 2010). Broad adaptation initiatives are underway, which may affect these projections, including the 2014 Chesapeake Bay Watershed Agreement, U.S. Army Corps of Engineers Bay Islands Creation Plan, Next Generation Adaptation Plan, 2031/2045 Greenhouse Gas Mitigation Plan, and Maryland's Coastal Resiliency Assessment (Canick et al., 2016).

Out of the many available sea level rise tools, four options applied to this assessment's scope. The MAGICC Model is a detailed projection model based on 43 future greenhouse gas concentrations and temperature change projections (Beusch et al., 2022); however, this model is better suited to approximating global climate as opposed to local, community-level climate projections. Similarly, NASA's sea level rise projections (NASA, 2025) build off the MAGICC model by incorporating multi-scenario and temporally

adjustable capabilities, but it too is better aligned to global climate assessments. FloodAdapt, a proprietary tool geared toward adaptation planning (Deltares, 2025) may be useful for future partner planning but its data do not align with NOAA's open access standards.

NOAA's sea level rise data from the Office of Coastal Management (NOAA Office for Coastal Management, 2024) were chosen for this assessment due to their spatial scale, their local relevance, and fact that they were designed to assess coastal flood frequency and sea level rise with a particular focus on wetland migration and near-term climate projections through 2050. However, they do not account for land subsidence. NOAA's sea level rise data incorporate local tide gauge data from the Chesapeake Bay to create and interpolate tidal surfaces, regularly updating the database with new elevation models (including a Maryland update in 2019) and sea level rise predictions (most recently updated in 2022). NOAA tide gauges in Baltimore, Annapolis, Tolchester Beach, and Chesapeake City, Maryland, are used for interpolating the tidal surface in this study area (see Figure 25). This dataset models the extent of future sea level rise, hydrodynamic connectivity, flooding frequency, and wetland loss and migration.

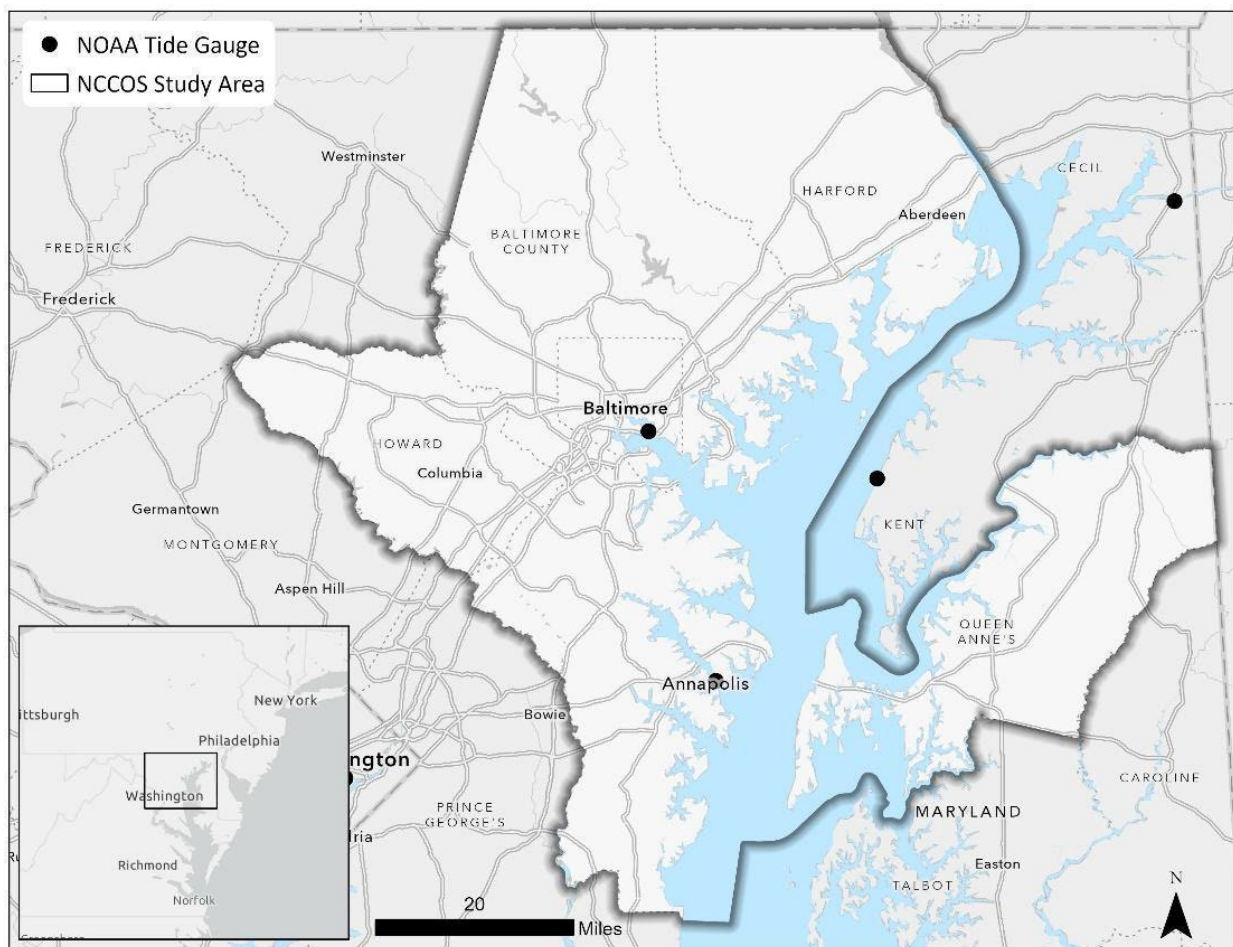


Figure 25. NOAA tide gauge locations in and around the study area used for creating the projected tidal surface.

Coupling NOAA's sea level rise data with projections from the Maryland Climate Change Commission (MCCC) provides a clearer picture of how the Chesapeake Bay coastline will evolve over the next 25 to 75 years. The MCCC directs analyses for the state to use a 2-ft sea level rise by 2050 and a 5-ft sea level rise by 2100 (Boesch et al., 2023), depicted in polygons of projected flooding in Figures 26 and 27, respectively. Figure 28 uses highlighted areas to show where the most significant changes are expected between these two projections. It is important to note that these projections are based on current climate commitments (as of 2023) and do not incorporate scenarios like those under the Paris Agreement or increasing-emissions scenarios. The projections do account for potential ice loss, using the worst-case scenario for ice melt based on current climate policies (Boesch et al., 2023). While useful, these projections should be ground-truthed at the local level, as well as refined and updated over time.

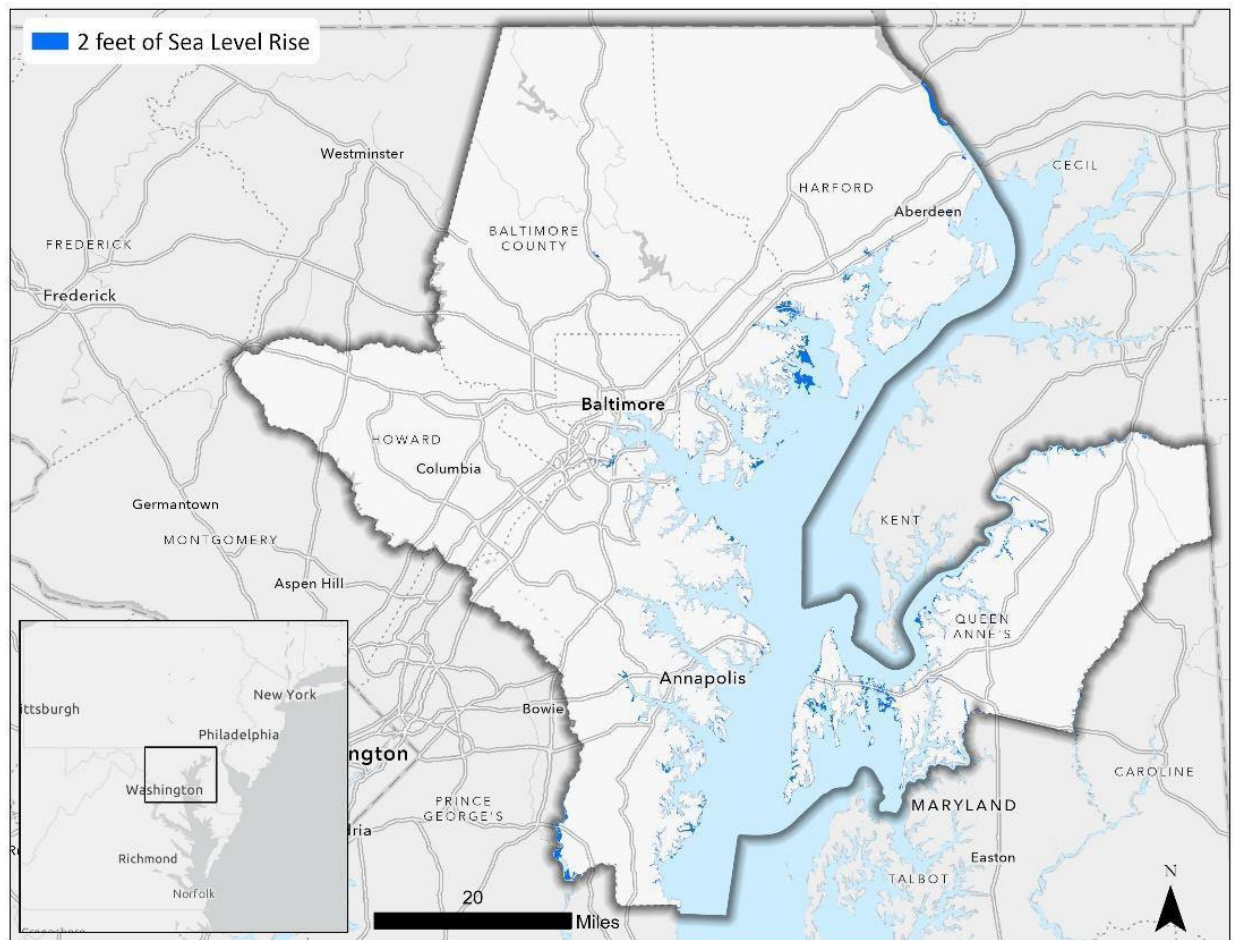


Figure 26. Sea level rise expected for 2050.

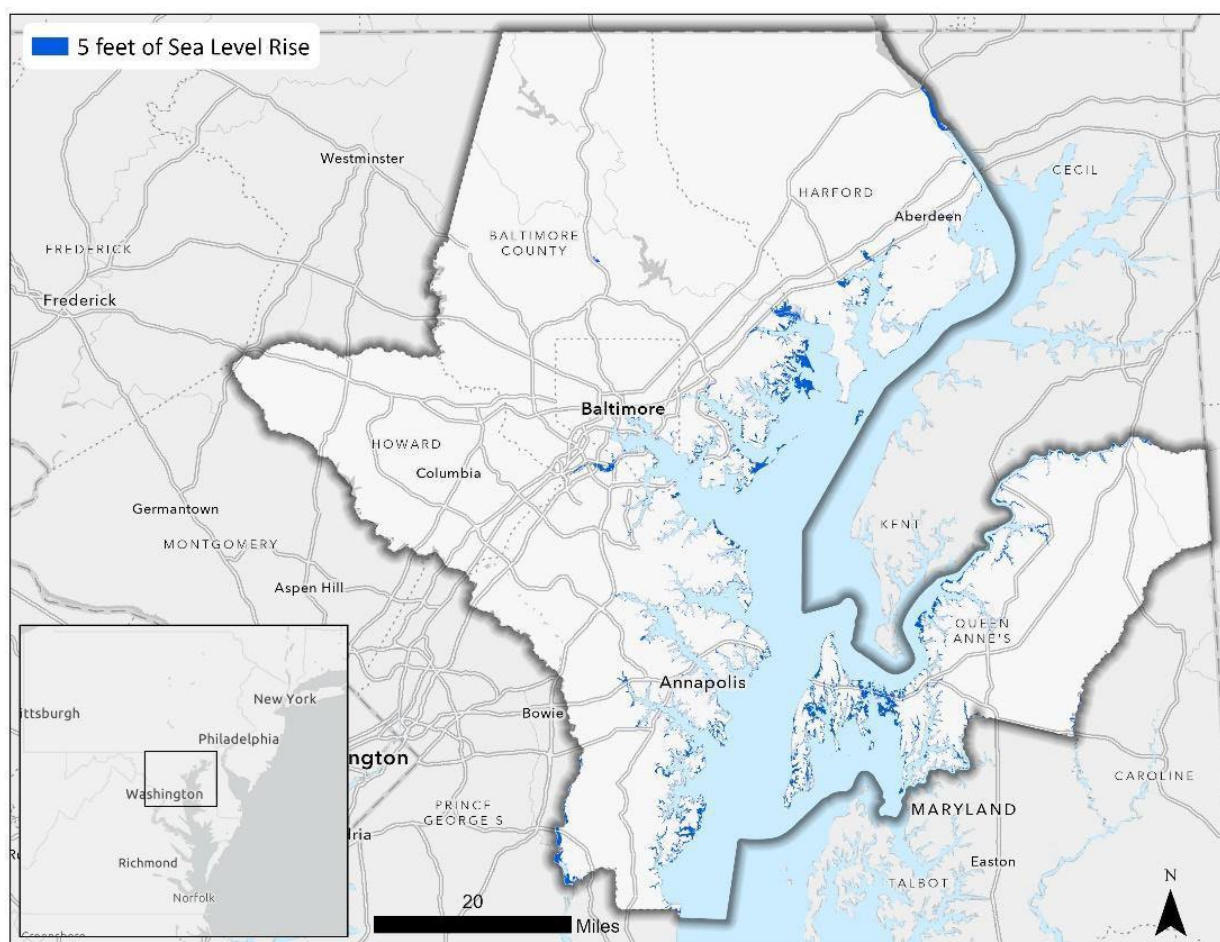


Figure 27. Sea level rise expected for 2100.

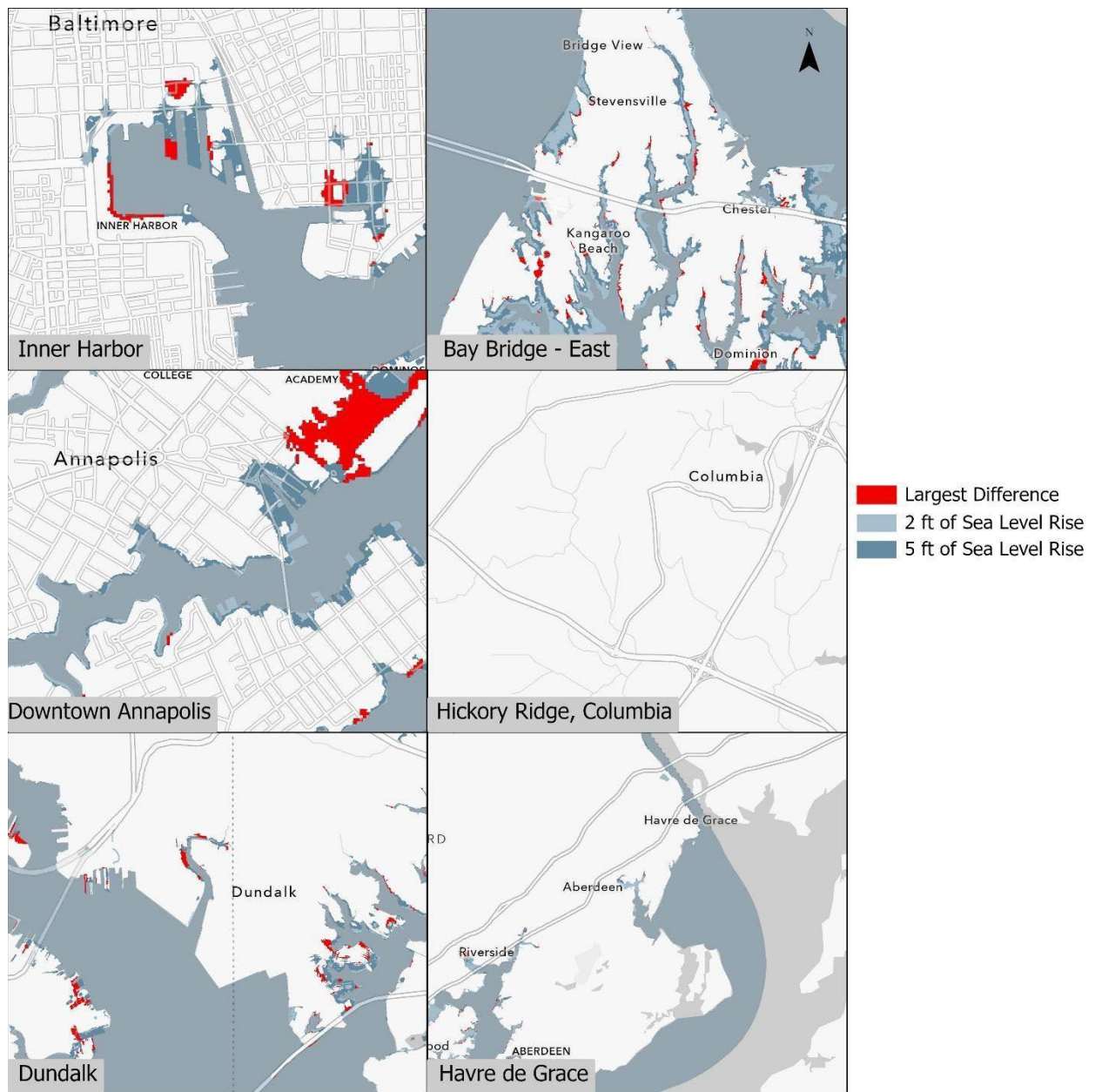


Figure 28. Displays current 2-ft, and 5-ft sea level rise, with areas in red displaying the locations that experience the most severe differences in sea level rise, within the top 20% of change.

2.4.3 Storm Surge

Storm surge is the influx of water along coastal areas caused by strong winds and shifting atmospheric pressure during storms. The Chesapeake is particularly vulnerable to storm surges from tropical storms and hurricanes with southeasterly winds (Boesch et al., 2023) and can raise water levels over 15 ft (NOAA Meteorological Development Lab 2025).

Two main storm surge models are relevant to this study area. The first is the Super-Fast INundation of CoastS (SFINCS) model, developed by Deltares. SFINCS is an open-source compounding flooding model that simulates water movement during extreme events, factoring in storm surge, wind-driven waves, precipitation, physical barriers, and upstream river discharges. Its multi-hazard approach allows for large-scale flood risk analysis and adaptation planning (Leijnse et al., 2021). SFINCS overlapped with other components of this study, so it was not directly applied here (Leijnse et al., 2021).

This study uses the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) Model, developed by the National Weather Service. The SLOSH model estimates storm surge heights and associated inundation based on historical, hypothetical, and forecasted storm conditions (NOAA Meteorological Development Laboratory, 2025).

SLOSH produces two key data products to visualize flooding. The maximum envelope of water (MEOW) represents the worst-case scenario storm surge for a given hurricane category and landfall scenario. Maximum of MEOWs (MOMs) combine all possible MEOWs for a location simulating the maximum inundation from a “perfect storm” scenario. This assessment uses MOMs data for the Maryland Chesapeake Bay basin under high-tide conditions, representing the highest simultaneous potential storm surge and inundation heights (see Figures 29 and 30) (NOAA Meteorological Development Laboratory, 2025). The SLOSH model focuses on storm surge and does not account for rainfall, river flow, or wind-driven waves. Figure 31 illustrates surge in highlighted neighborhoods, and Figure 32 shows differences in predicted inundation (in meters) between Category 2 and Category 4 storms around Kent Island.



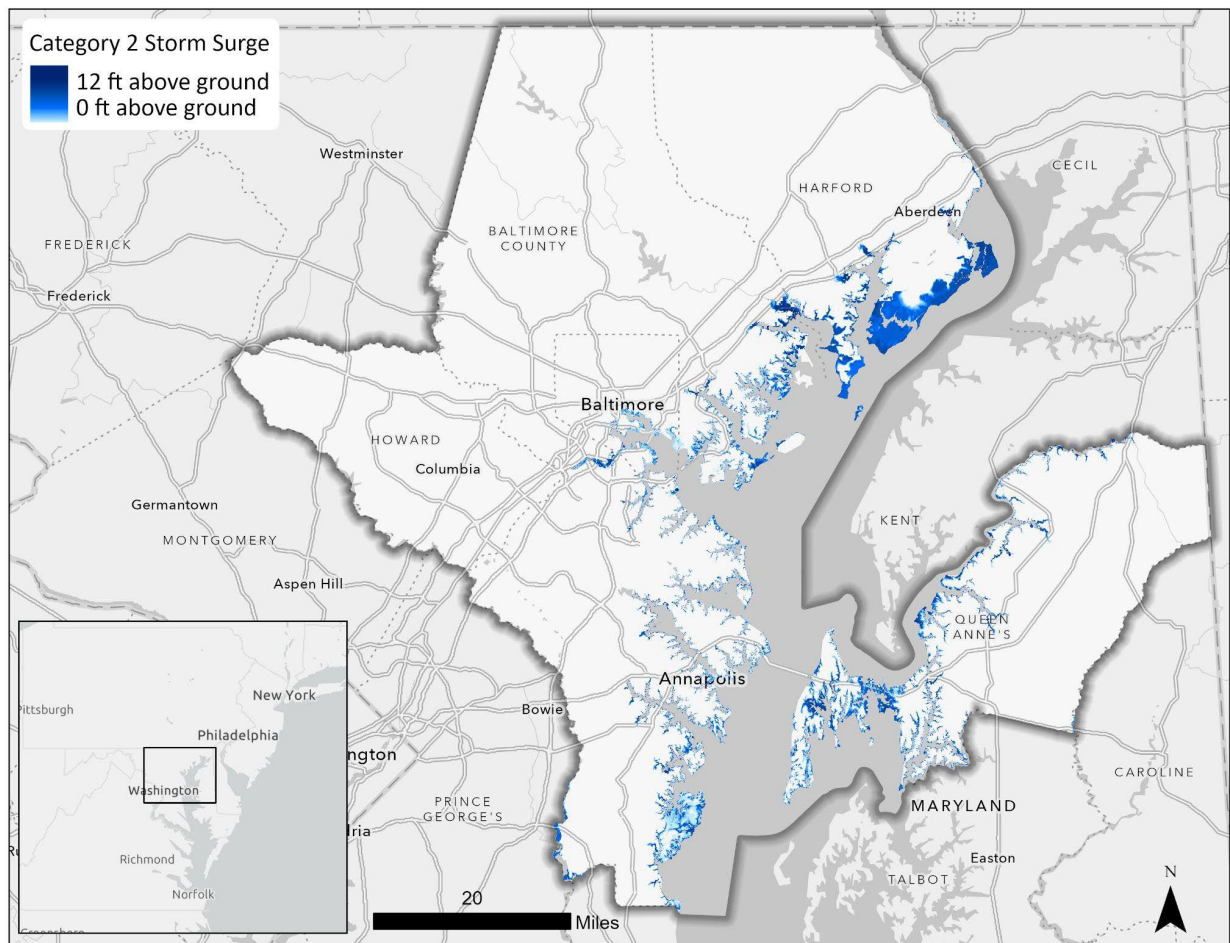


Figure 29. Category 2 storm surge for the study area.

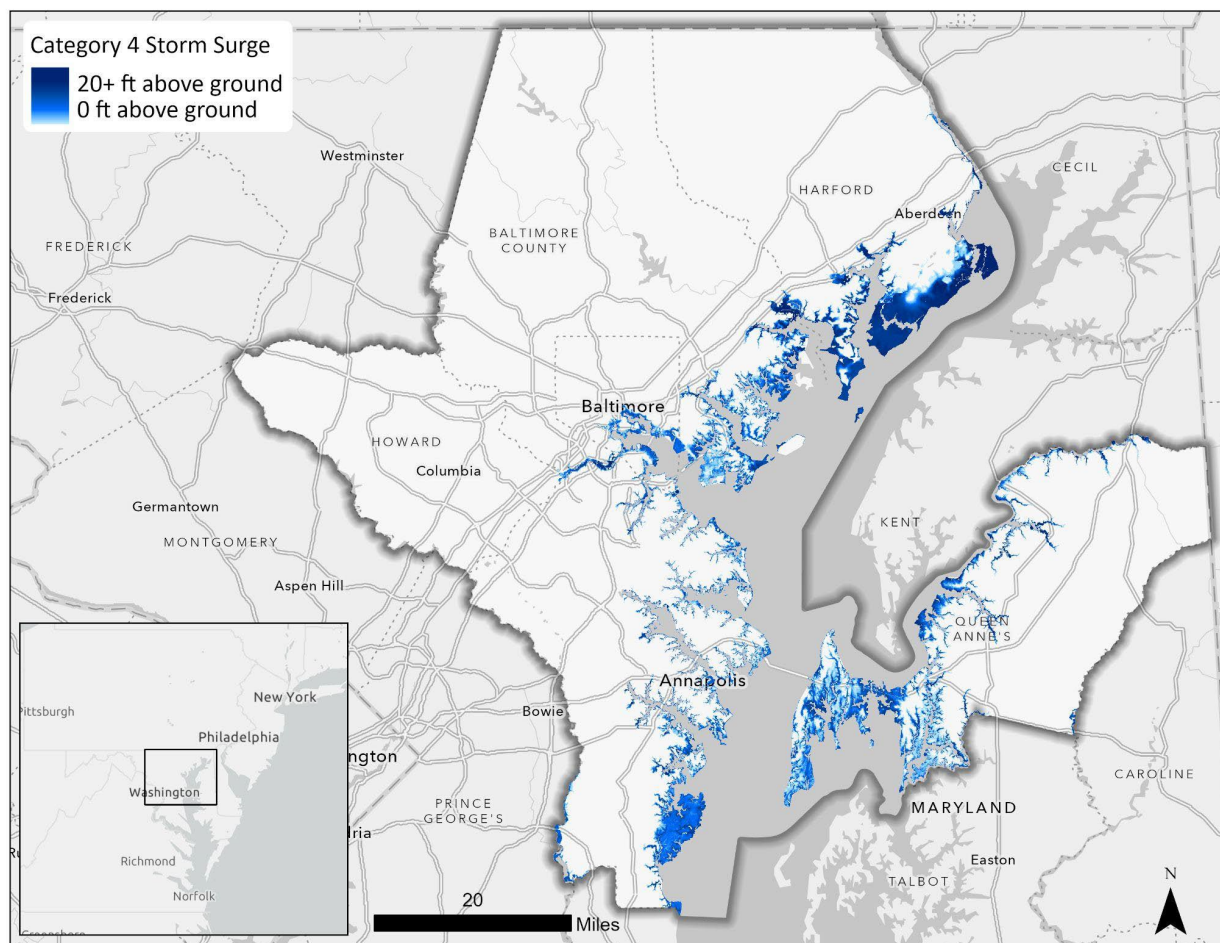


Figure 30. Category 4 storm surge predicted for the study area.

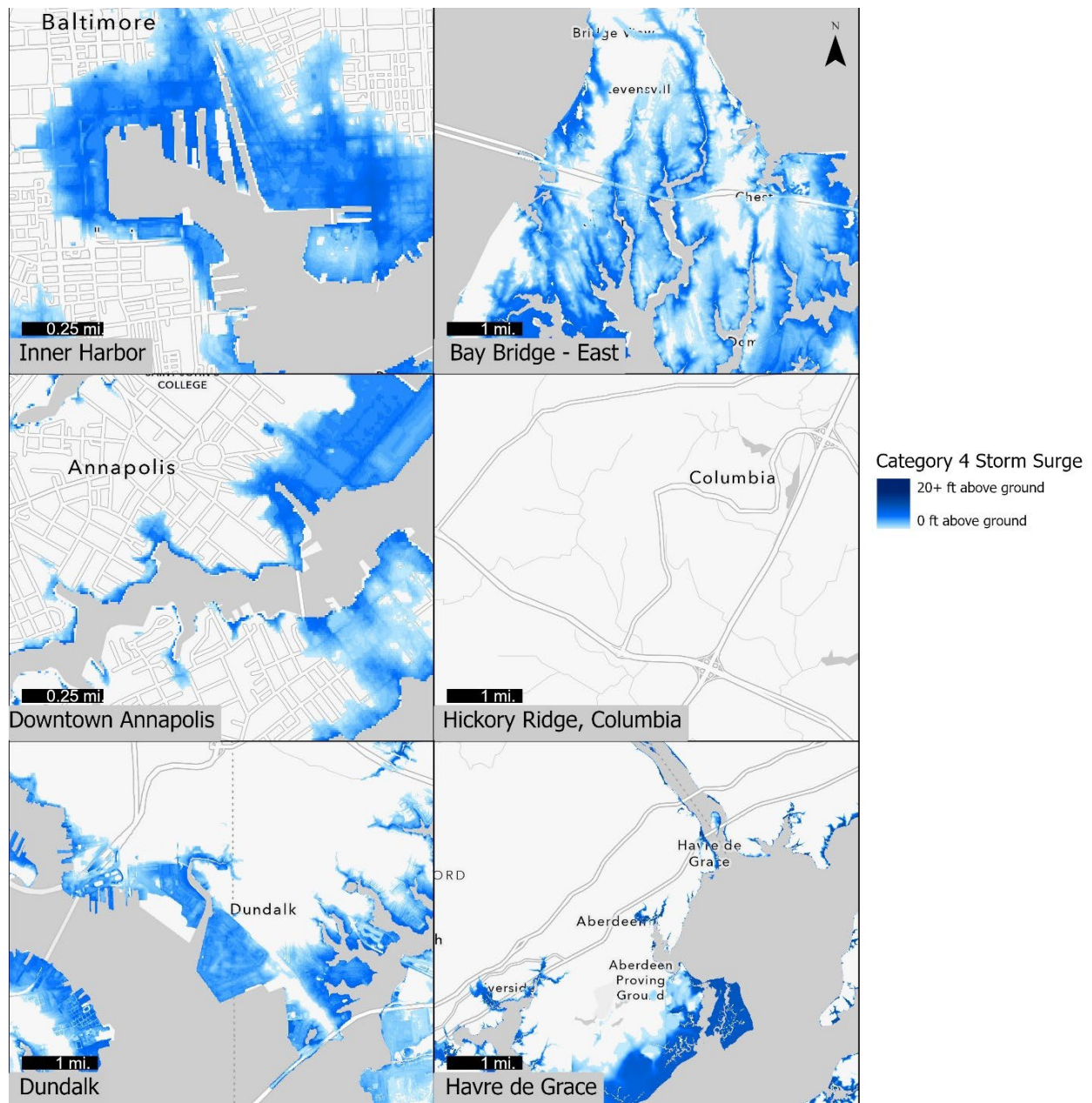


Figure 31. Storm surge predictions from a Category 4 storm in the highlighted areas.

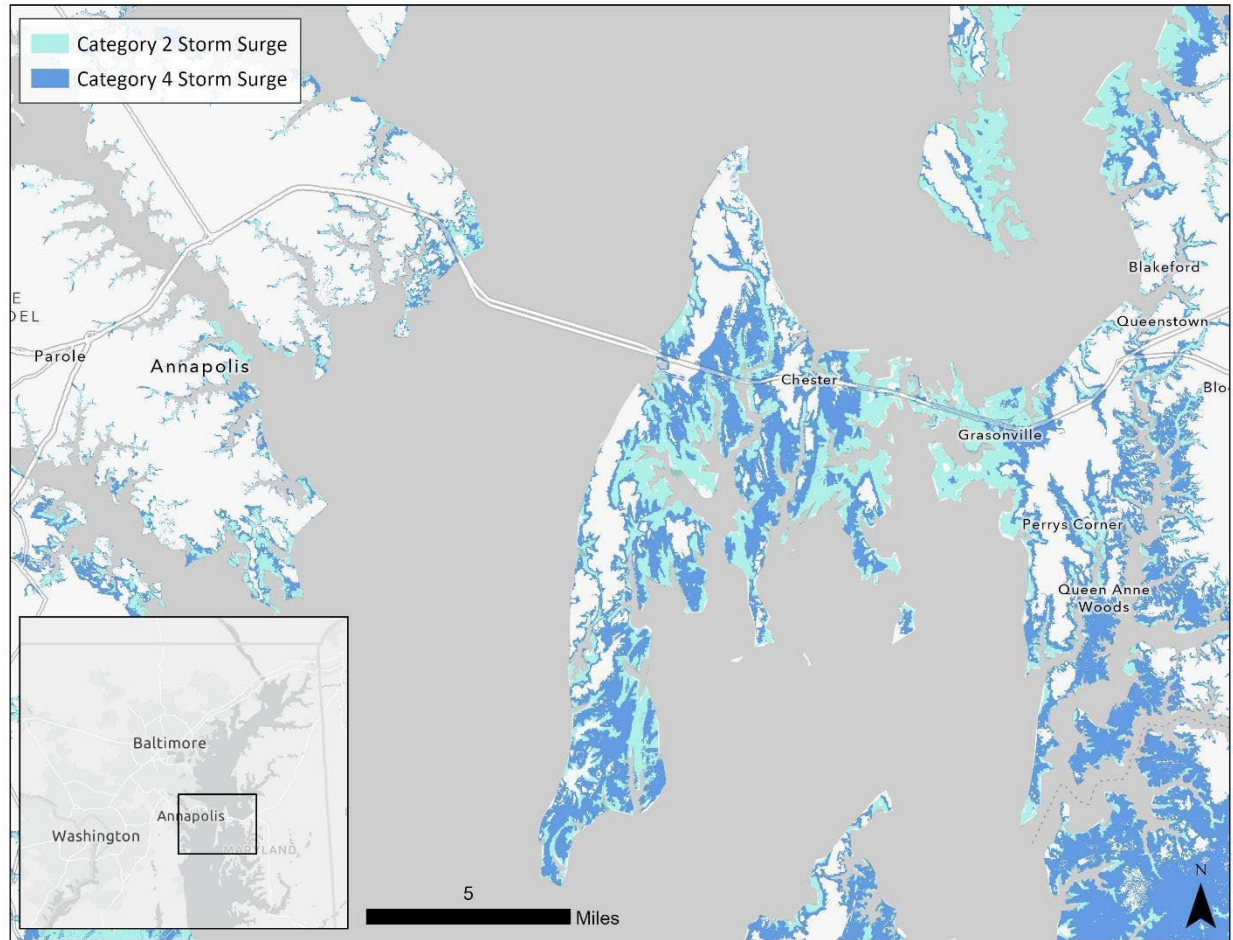


Figure 32. Storm surge comparison between Category 2 and Category 4 hurricanes, focused on the Kent Island portion of the study region.

2.4.4 Compounded Flooding: Synergy in Flooding Forces

Modeling combined floodwaters is a logistical and mathematical challenge. First, interaction effects between the three types of flooding must be considered and modeled simultaneously; this is usually done in the context of individual storm parameters. These interactive models assess the synergistic effects of multiple flooding forces (e.g., Wang et al., 2015). Second, the models for rainfall (and weather more broadly) are probabilistic and near-term, while the models for sea level rise and storm surge (and climate more broadly) are deterministic, looking decades into the future. The science of flooding has yet to successfully address these issues. A review of 271 studies looking at compounded flooding yielded the following suggestions for future research: 1) adopt consistent terminology and approaches; 2) expand the geographic coverage of research; 3) pursue more inter-comparison projects; 4) develop modeling frameworks that better couple dynamic Earth systems; and 5) design urban and coastal infrastructure with compounding in mind (Green et al., 2025). While some of these recommendations are aimed at researchers to someday create the desired compounded flooding model, some are hints at how to take actions now while those models are created.

In areas with sufficient flow data, a grid-based flow routing model like the EPA's Stormwater Management Model can be used with varying sea level rise and storm surge conditions as boundary conditions (Qiang et al., 2021). This is both a data-intensive and computationally intensive process, and models are usually at the neighborhood scale at the largest; some of these neighborhood-scale models are being created as part of the Baltimore Social-Environmental Collaborative (Baltimore Social-Environmental Collaborative, 2025). However, a city-wide "wall-to-wall" model does not exist yet, and the suburbs do not have sufficient stormwater infrastructure data available to run the Stormwater Management Model.

Similar work in the area has demonstrated creativity in dealing with converging floodwater models. In Norfolk, Virginia, a transition zone index was developed to help policymakers determine their primary flood driver (stormwater or tidal water) and choose adaptations accordingly (Shen et al., 2019). They found that tidal fluxes have an influence on both overland and piped stormwater flow, and thus, they chose historic hurricane conditions for setting the stormwater model conditions. Other work in the watershed modeled historical storm predictions, using river discharge as part of a grid-based inundation model as a way to approximate the contributions of stormwater rainfall to flood heights in Washington DC (Wang et al., 2015). This scenario-based approach allows the model to flatten probabilistic weather predictions by using measured weather outcomes at a particular time.

Combined floodwater modeling needs investment and development to meet stakeholder demands, but future work might be able to bridge the gap between existing models and demand. Using boundary conditions set to future climate scenarios for rainfall as well as modeling specific storms are both successful strategies deployed in the watershed but not at the study-area scale. Rescaling these types of studies to a region as large as the six-jurisdiction study region here is another technical and data management challenge but not insurmountable should funds be directed for that purpose. Given these challenges, this study presents co-occurrence of several flooding risk types in the bivariate choropleth analysis section as a means of demonstrating the need for more complex modeling (section 3).

2.5 Urban Heat

As climate impacts continue to cause changes and shifts in local weather conditions, increasing heat, especially in urban environments, is a growing public health concern (Tong et al., 2021). Importantly, heat impacts communities disproportionately and interacts with structural issues such as proximity to cooling centers, as well as resident age, health conditions, energy costs, etc. Additionally, urban heat impacts are often felt long after the sun sets, impacting communities across consecutive days with little respite (Tong et al., 2021).

The urban heat island effect is a phenomenon where urban areas, with impervious, heat-retaining surfaces such as asphalt and concrete experience higher temperatures than rural surroundings (Heaviside et al., 2017). Additionally, minimal vegetation in urban environments reduces the natural cooling effects of shading and evapotranspiration, exacerbating the heat accumulation (Heaviside et al., 2017). The presence of vehicles, industrial activities, and air conditioning units further contributes to the urban heat island effect by releasing heat into the urban atmosphere. As a result, cities can be several degrees warmer than nearby rural areas, particularly during the evening and night (Figure 33).

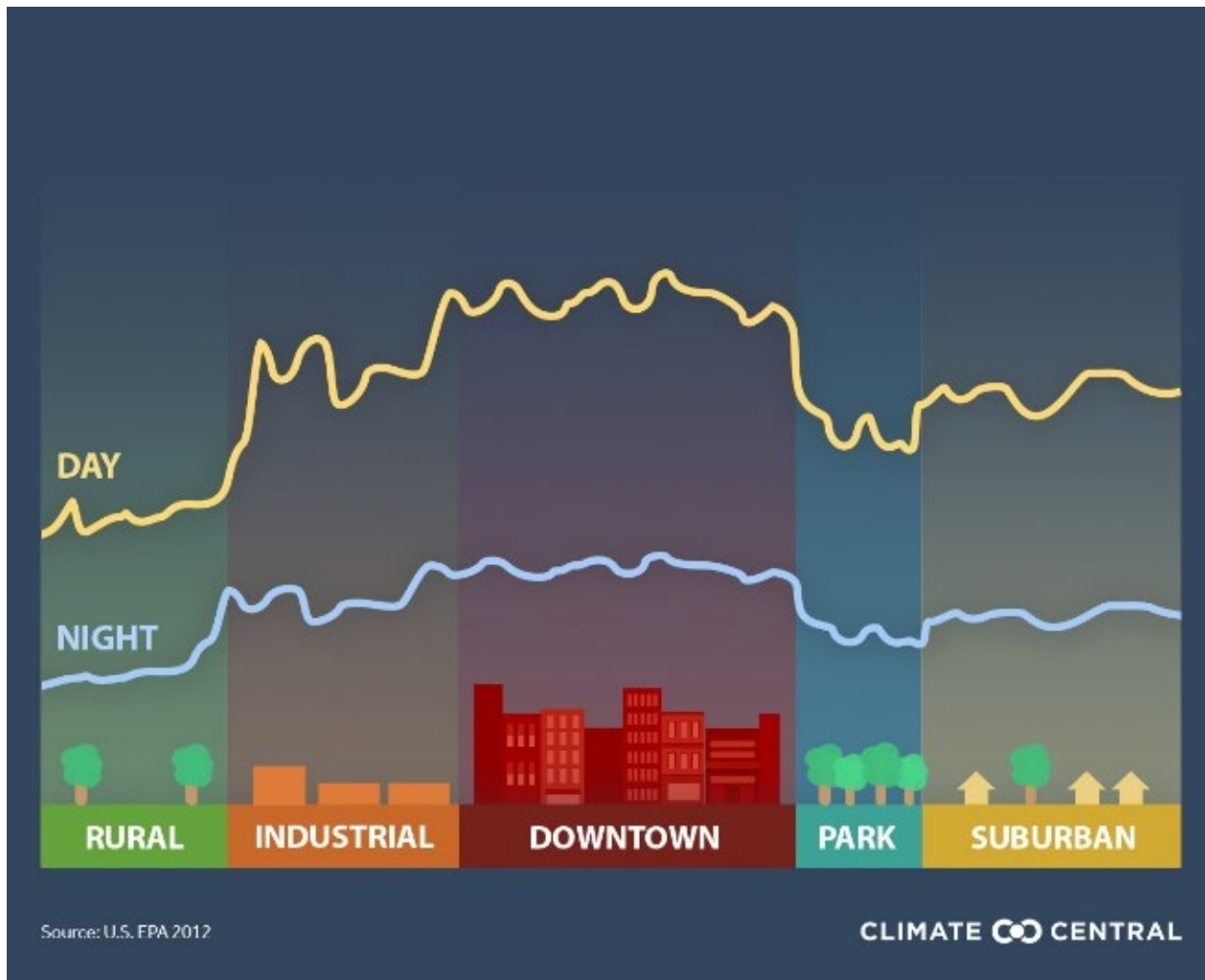


Figure 33. Infographic on how urban heat works around various land cover types. Source: Climate Central.

The urban heat island effect can significantly impact dense neighborhoods, causing compounding risk factors (Heaviside et al., 2017). These areas often experience limited green space, reduced tree cover, higher population densities, and a greater proportion of impervious surfaces—a combination of factors that contribute to elevated temperatures, particularly after sunset. Furthermore, the absence of sufficient cooling infrastructure heightens urban residents' susceptibility to heatwaves and extreme temperatures. This disproportionate exposure can cause health impacts such as heat exhaustion, heatstroke, and worsened respiratory and cardiovascular conditions.

For the study area, the research team used a remotely sensed urban heat analysis based on Landsat data (USGS, 2024a). This analysis allowed for the evaluation of relative spatial variations in urban heat across the entire study area at a 30 × 30 m resolution (Figure 34). An urban heat index was created by averaging the resulting raster data for each block group (Figure 35).

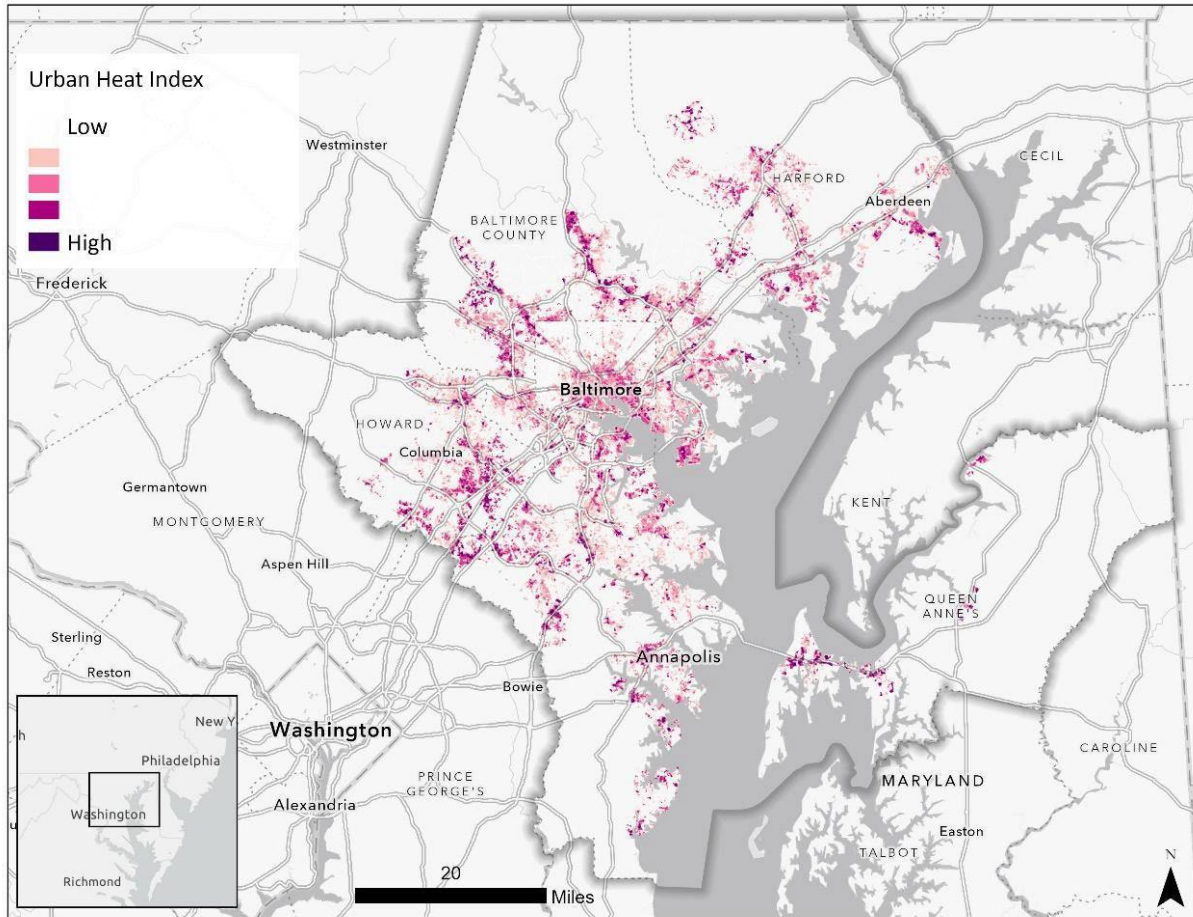


Figure 34. Urban heat index across the five-county region, based on Landsat data.

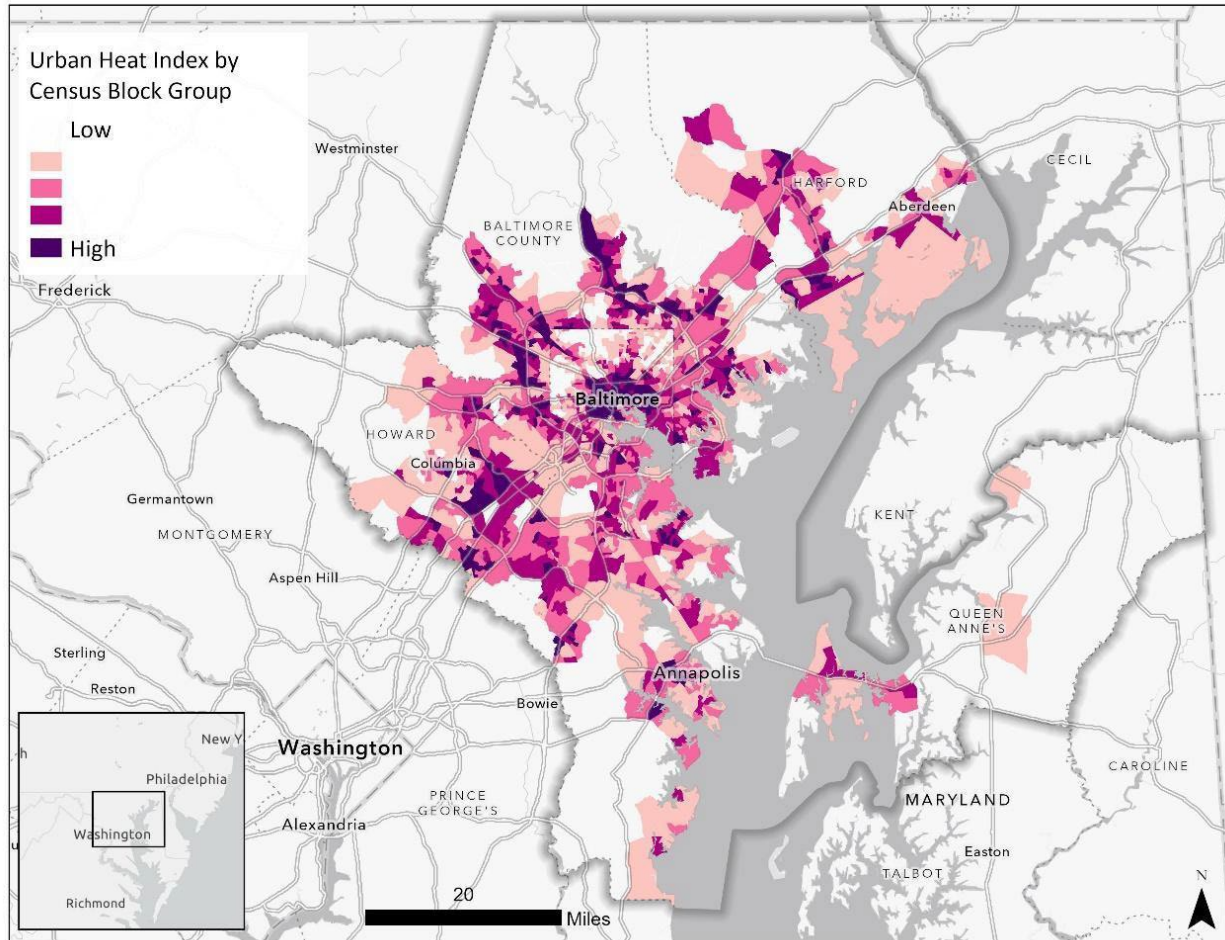
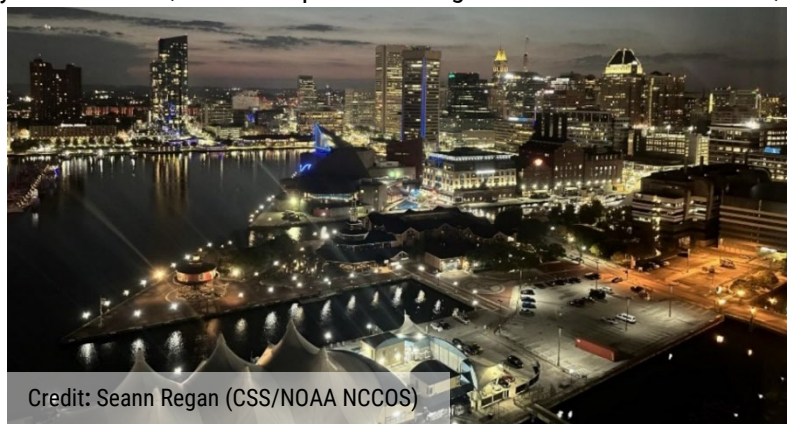


Figure 35. Urban heat index aggregated to census block groups, based on Landsat data.

The different data sources provide the means to answer different research questions based on whether one needs to prioritize quantitative, spatially resolute data, or better spatial coverage. With additional research, these data sources can potentially be integrated into a single model (Shandas et al., 2019). For now, having data options allows high-resolution visualizations necessary for identifying specific areas with urban heat concerns while also providing estimates in the wider area; future expansions in monitoring could provide high-resolution data across the whole study area, which would be particularly helpful in urbanized parts of the counties surrounding Baltimore City. The resolution shows best when displayed for distinct neighborhoods (Figure 36).



Credit: Seann Regan (CSS/NOAA NCCOS)

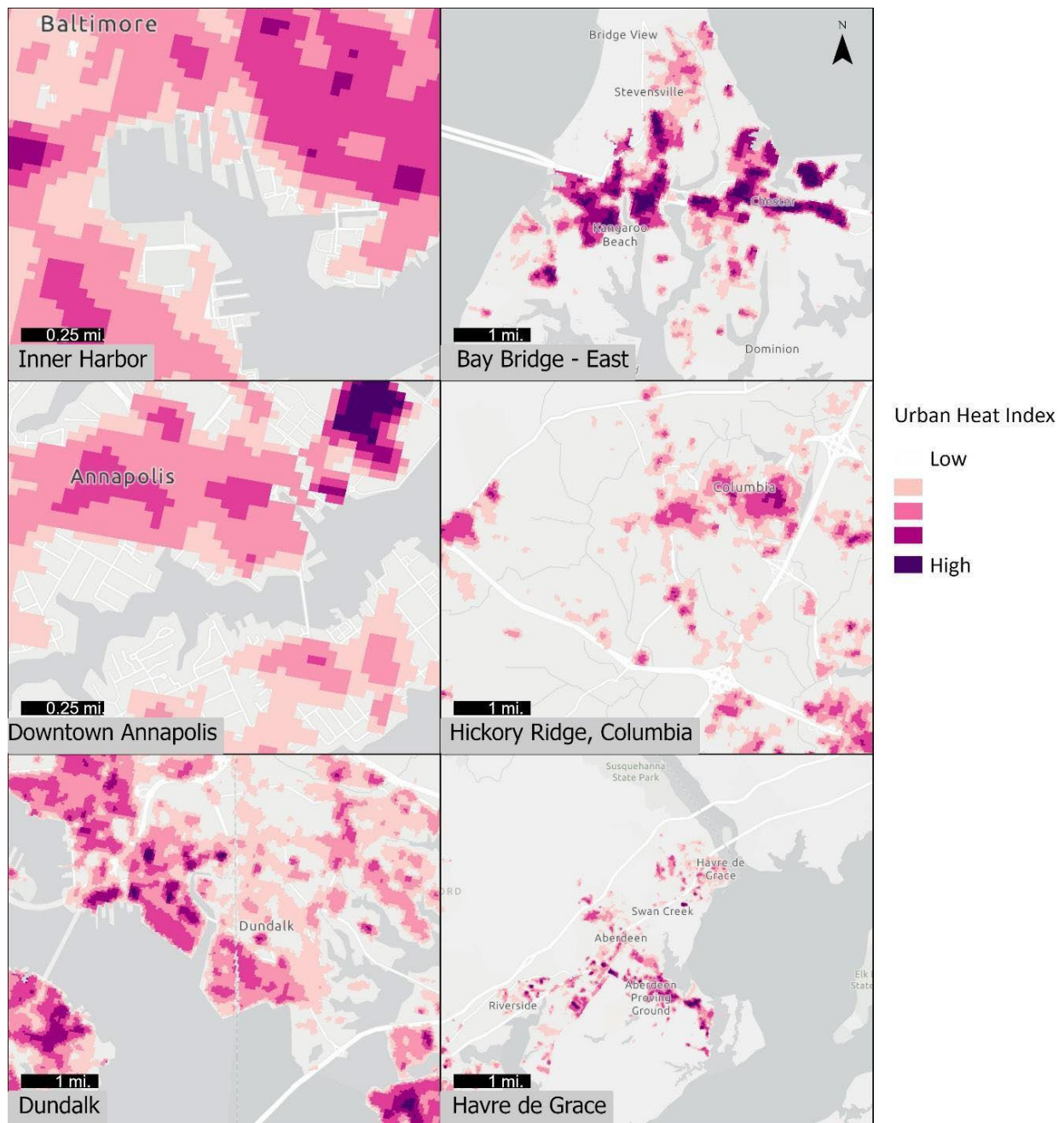


Figure 36. Urban heat index at select locations across the study site, based on Landsat data.

2.5.1 Urban Heat Related to Public Health Recommendations

Urban heat has an important threshold of 90°F; discussion of urban heat needs attention to this threshold specifically, and therefore, a more detailed discussion is included for this component than for others. A 90°F threshold is where continuous heat exposure becomes dangerous to human health, so should be depicted as a key inflection in urban heat data ranges (Federal Emergency Management Agency, 2024). Heat-related illness is more common above 90°F as the body struggles to regulate internal temperature,

leading to potential increase in heat exhaustion, stroke, and dehydration. As a result, health researchers use this threshold as the point where air conditioning becomes necessary and outdoor work behaviors must be altered (Hoehne et al., 2018).

To visualize this threshold in the study area, Figure 37 shows 90°F in the evening depicted in red. These high-resolution temperature measurements were collected by the NOAA Climate Program Office, which employed vehicle transect data, weather data, and ground station measurements to analyze urban heat (Shi et al., 2021). While quantitative, highly accurate, and spatially resolute, this analysis was limited to the city of Baltimore and a relatively small time horizon, so it can address only downtown neighborhoods, not the whole study area.

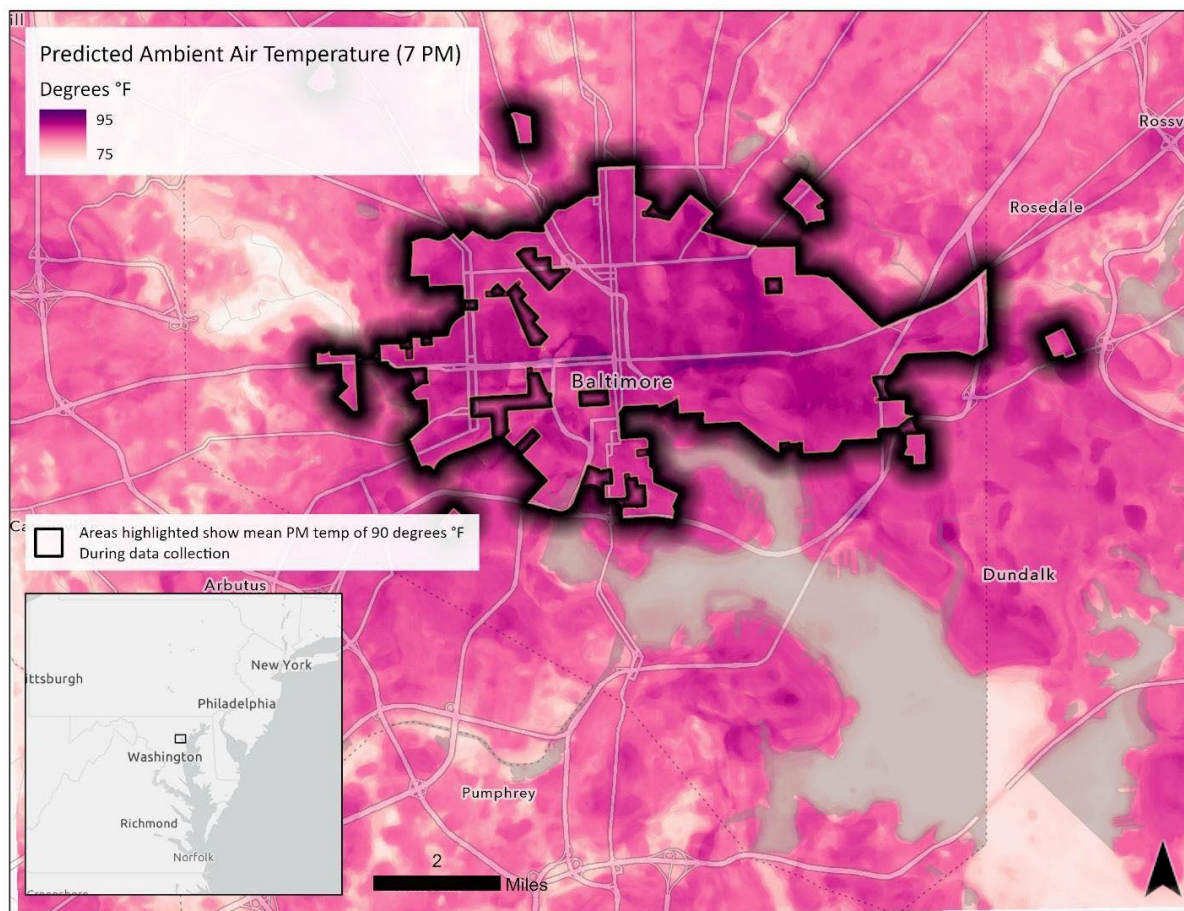


Figure 37. Average evening (PM) temperatures logged in Baltimore City. Anything over 90° (highlighted in red) has increased public health impacts.

While urban heat impacts can be felt across the whole study area, small-scale dynamics around green space have cooling effects. Conversely, areas with high impervious surfaces become hotter and retain heat longer (Li and Zhou, 2019). Figure 38 shows the normalized difference vegetation index, a remotely sensed measure of green space alongside the urban heat index to show where these small-scale dynamics are at play.

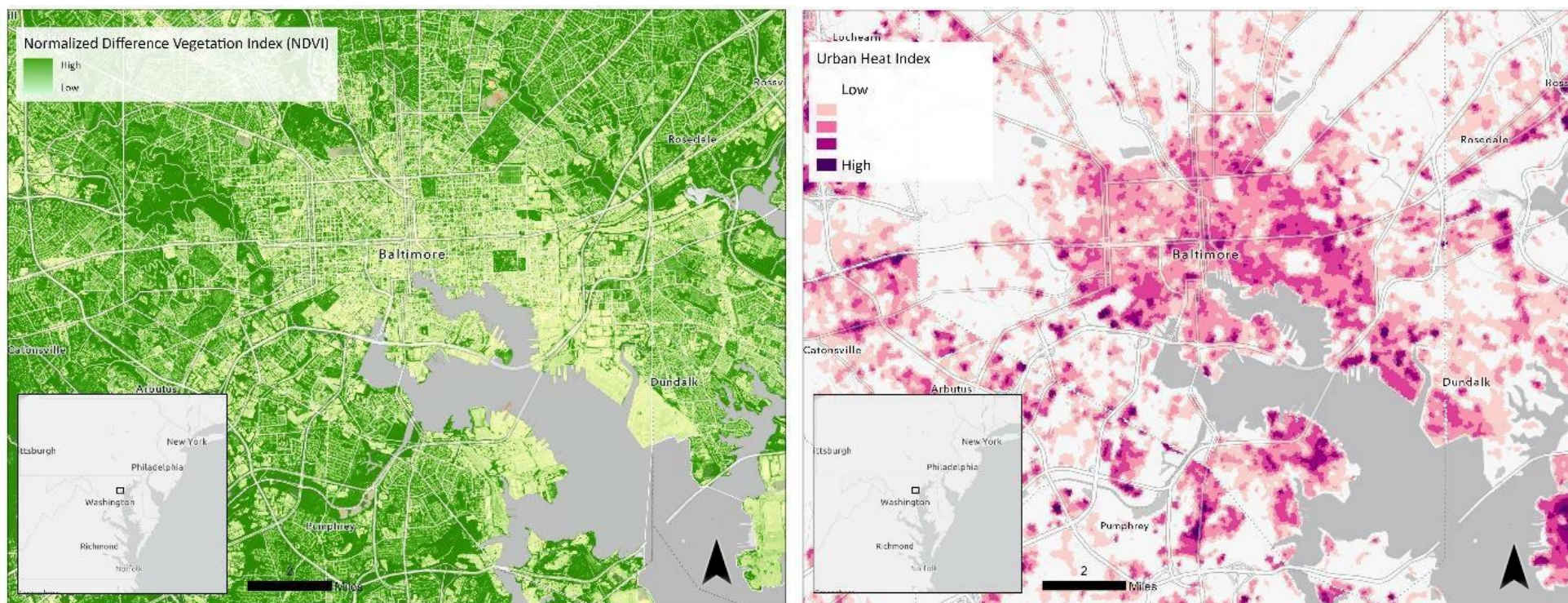


Figure 38. NDVI compared to urban heat index data in the Baltimore region. NDVI = normalized difference vegetation index.

Strategies such as increasing urban greenery through the planting of trees and the creation of parks can provide much-needed shade and cooling, reducing surface and air temperatures (Baumeister et al., 2020). Ongoing initiatives in the region (e.g., iTree) include the promotion of green roofs and cool roofs, which reflect more sunlight and retain less heat by increasing surface albedo and thermal emittance, helping to reduce urban temperatures (Li et al., 2014). Urban planting programs in Baltimore have been effective at reducing urban heat in the area immediately around the plantings, but those tend to be in higher-income neighborhoods; efforts at more even spatial distribution could help some of the hottest areas (Anderson et al., 2023). Engaging communities in the planning and implementation of these strategies ensures that interventions are tailored to the specific needs and preferences of all neighborhoods, fostering resilience against the challenges posed by urban heat islands.

Part 3: Assessing Co-occurrence and Opportunities for Adaptation

The goal of collecting data for the various components and harmonizing their resolution of analysis is to layer them together and identify geographic areas where hazards and vulnerabilities overlap. In this case, the resolution of analysis is the block group, which is the resolution of the least-resolute data layer (population projections). This can be achieved through bivariate choropleth map visualizations where each component is broken into three categories representing the highest, middle, and lowest thirds of the data range. These are then visualized in contrasting colors that blend in areas of high values for both components. Figure 39 describes how to read the color system for these maps. Each corner of the legend represents data extremes for one or both of the components.

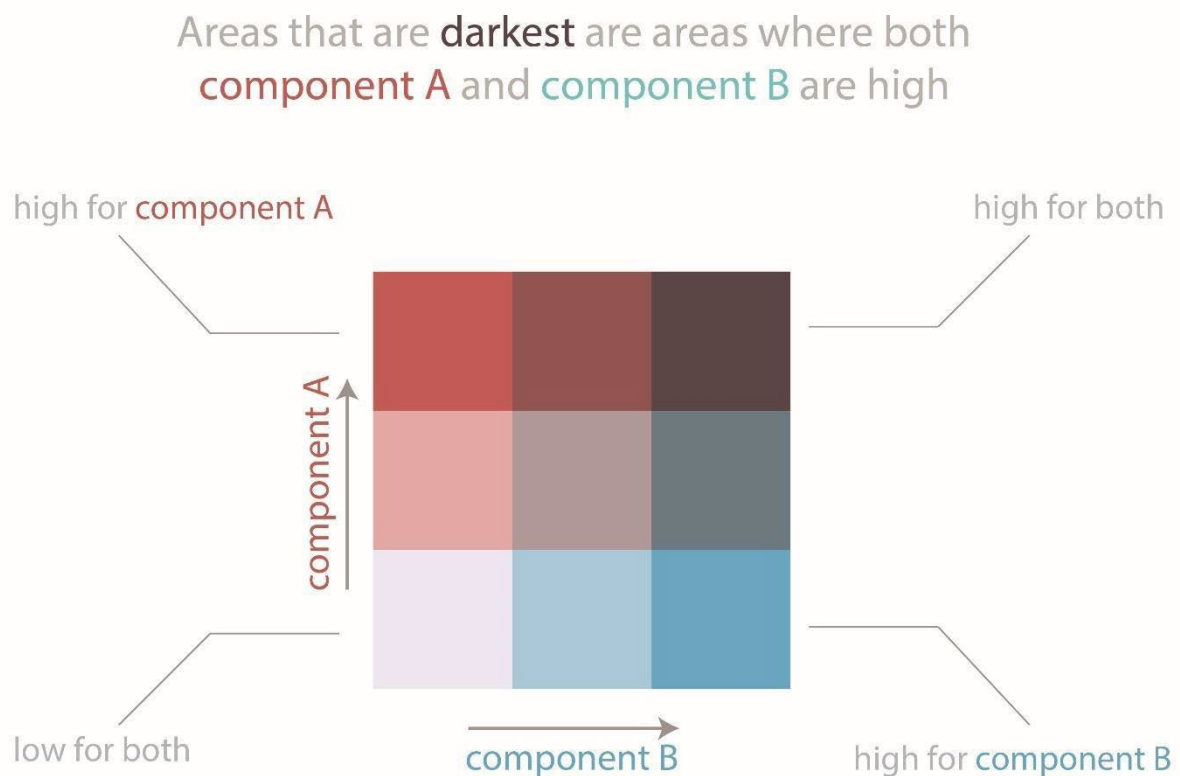


Figure 39. How to read a bivariate choropleth map.

This section presents bivariate comparisons that were chosen during a workshop at a Baltimore Urban Waters Partnership meeting as relevant to regional research and adaptation efforts within the priorities identified during the stakeholder engagement process (Table 1). During the workshop, Table 1 was reviewed, the available data were presented, and then the participants suggested which combinations of data were most important to display here. There are myriad combinations of data possible; data are archived here so data users can visualize what suits their application best:

<https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/HZDQEF>

Second, there is an analysis of how nature-based infrastructure is spatially related to key hazard components in order to address research prioritized by regional climate stakeholders (see Table 1).

3.1 Co-occurring Vulnerabilities, Exposures, and Hazards

3.1.1 Population Density Projections and Hazards

This section highlights co-occurrence of projected population density for 2050 with urban heat and flooding profiles. Urban heat and stormwater flooding are visualized across the entire study area, while sea level rise and storm surge are visualized specifically for waterfront communities.

First, the combination of projected population density with urban heat (Figure 40) highlights higher-risk downtown areas along the harbor, as well as pockets in the northwestern suburbs along major highways. The block group containing downtown Columbia also emerges as high risk. Areas facing high growth projections should consider mitigation strategies at the small scale of urban heat dynamics—such as increasing green space through tree plantings and public water access as well as decreasing impervious surface through new paving materials and green architecture.



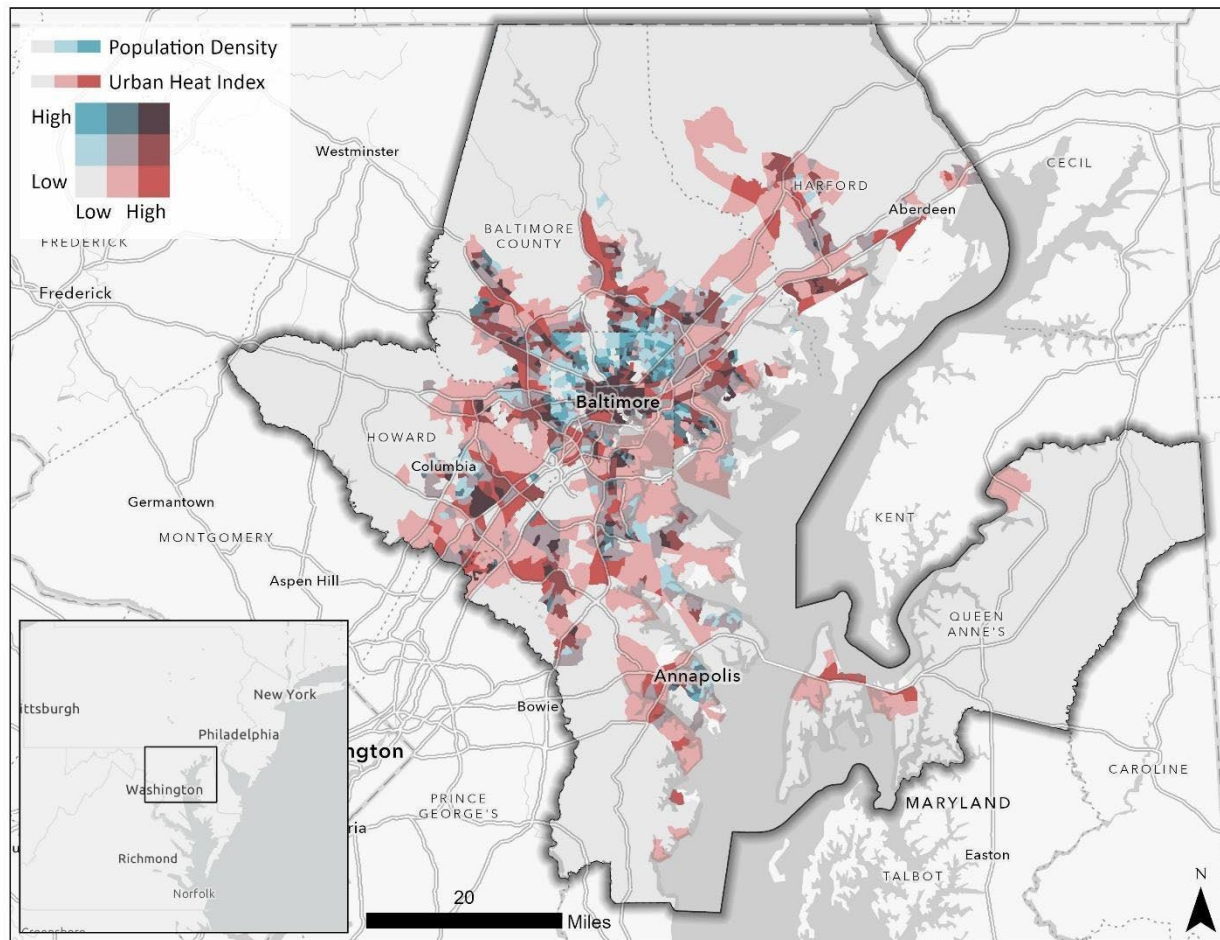


Figure 40. Population density projections in 2050 and current urban heat index displayed as a bivariate choropleth map.

A similar map (Figure 41), showing the intersection of population density projections and stormwater flooding potential, highlights many of the same areas near downtown Baltimore, the Inner Harbor, and the industrial port complex, along with patches in eastern Baltimore County. It also identifies historic areas of downtown Annapolis, extending from the main highway to the state capital building. Increasing population density in flood-prone areas requires careful planning for any new housing developments that population may require and associated engineered stormwater systems.

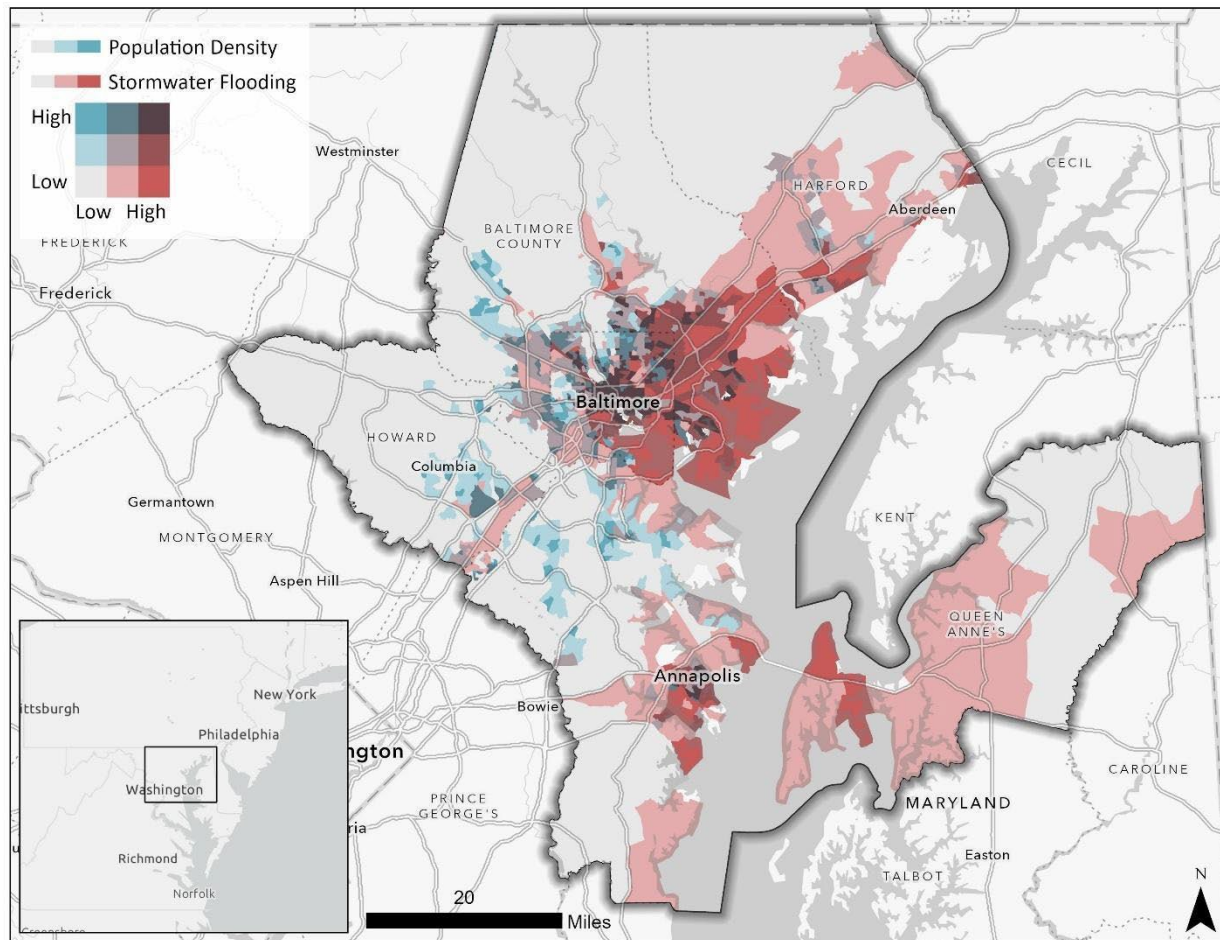


Figure 41. Population density projections in 2050 and current stormwater flooding potential displayed in bivariate choropleth.

For sea level rise and storm surge, a spatially constrained multivariate cluster analysis (run in ArcGIS Pro 3.4) on the relevant min-max normalized bivariate components identified clusters of block groups that contain similar predicted population density and flood risk. For sea level rise and projected population density, two clusters emerged, divided by the Bay (not shown). For storm surge and projected population density, six clusters emerged for the study area: two within the city and four that largely follow county boundaries, with Baltimore and Howard Counties combined into a single cluster. One city cluster represents both relatively high average predicted population density (average 8,133 people per square mile) and high storm surge (averaging 0.77 m), shown in Figure 42. This region, located in downtown Baltimore, is the only cluster to feature both storm surge concerns and high predicted population density. This area encompasses the neighborhood of Harbor East, which is currently undergoing rapid re-development, especially along the waterfront, as a means of directed economic development by the city (Dierwechter, 2008; Lehrfeld, 2025). Planning for future population needs, especially in this re-development context, requires incorporating flood protection into new building plans.

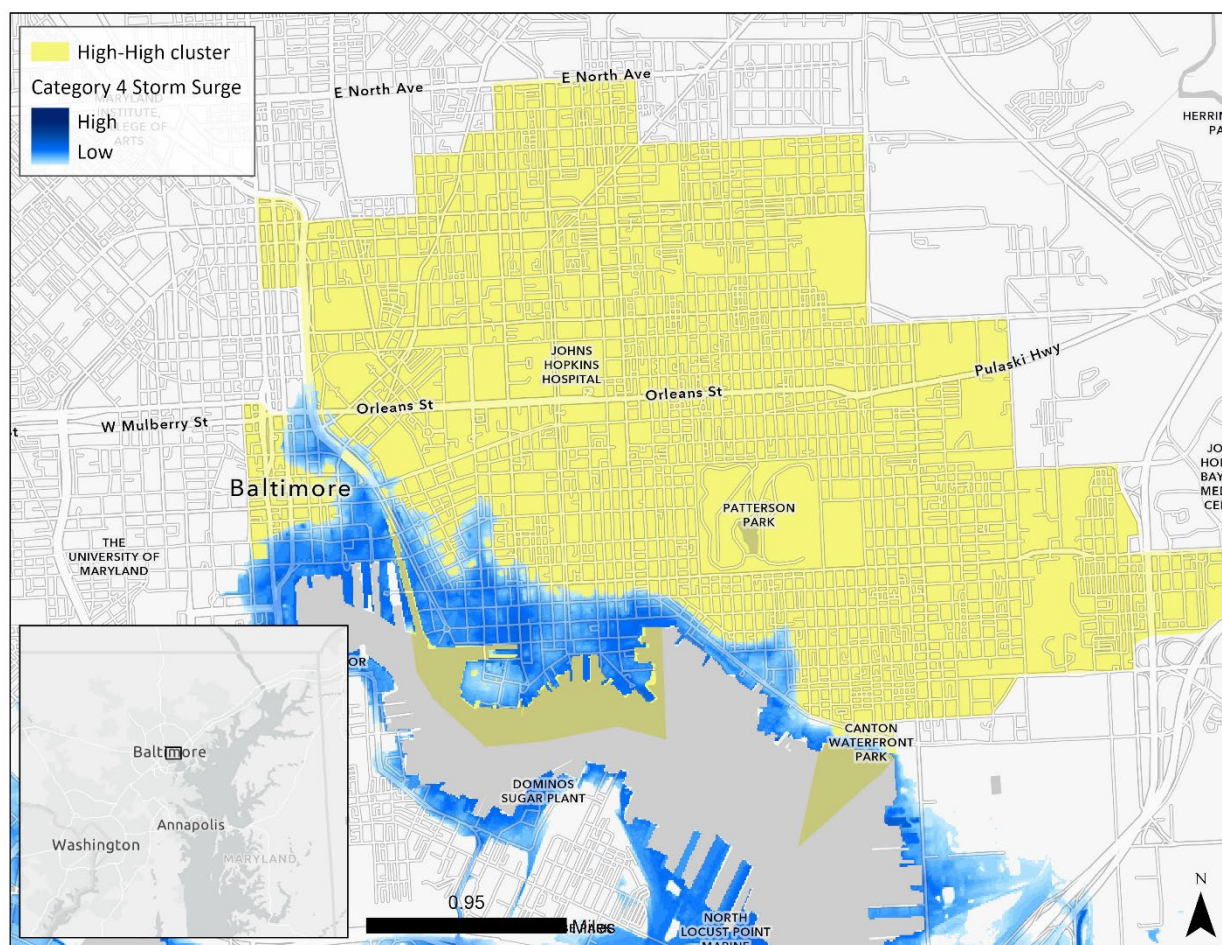


Figure 42. Current storm surge predictions shown on top of a cluster of high-density future population and high storm surge potential.

3.1.2 Compounding Exposures

This section examines how projected population density co-occurs with structural exposure and ecosystem service values. There are pockets of block groups with high projected population density and high structural exposure primarily in the urban core (Figure 43). These are often not contiguous clusters, but instead follow transit lines or highlight more industrial areas with core city-based infrastructure.

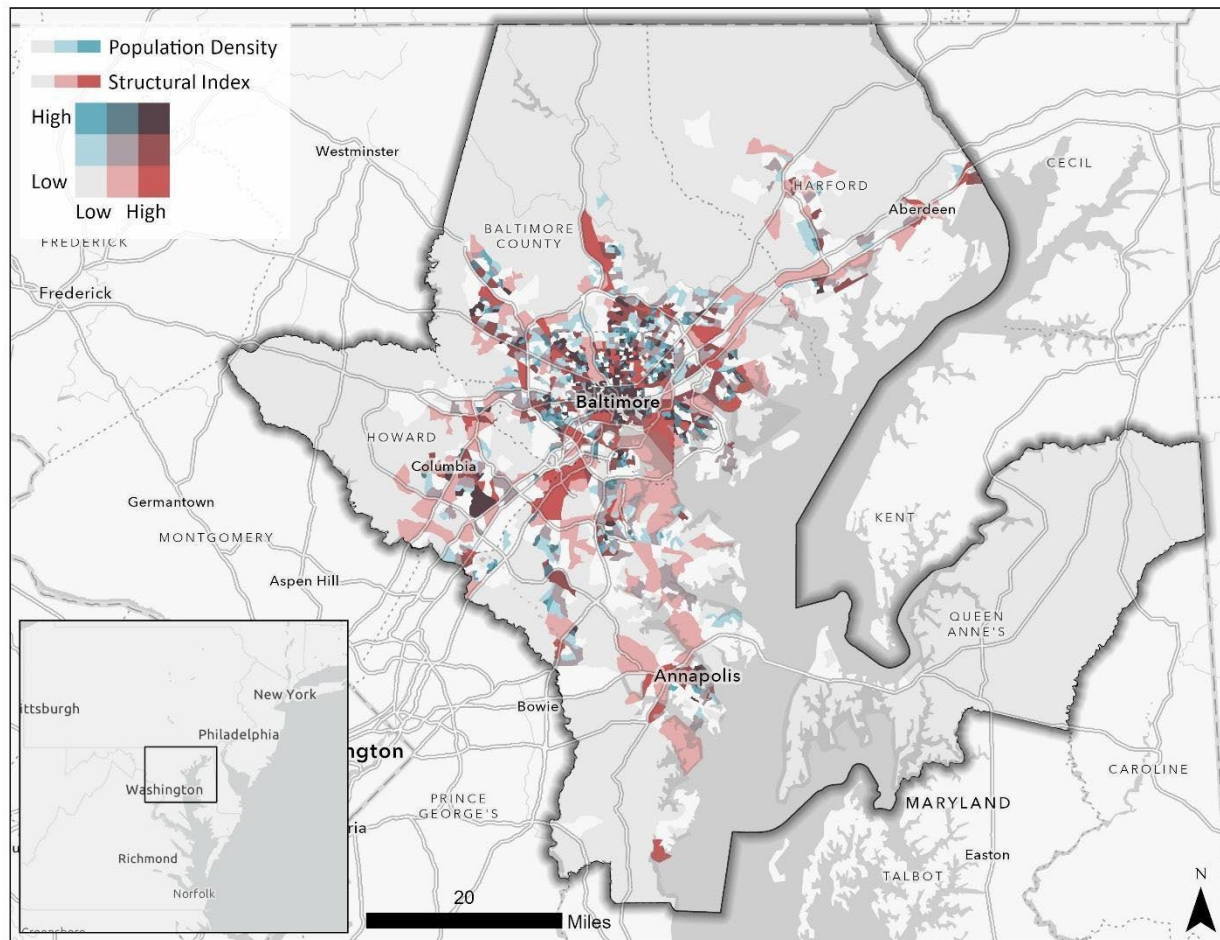


Figure 43. Projected population density in 2050 and current structural exposure bivariate choropleth.

The patterns between population density projections and ecosystem service values (Figure 44) are more smoothly distributed, with almost a gradient from high population density in the urban core to high ecosystem service values around the rural edges. There is a border of block groups along the highway leading through the northwest portion of the city where high projected population density and high ecosystem service value co-occur. These areas present opportunities for investments that protect ecosystem service values near large populations, allowing those services to directly benefit nearby residents. Proximity to highways and bus routes also provides regional access to ecosystem services that require physical visits, though this accessibility can increase visitor impacts on the sites. Note that the ecosystem service value data are available at 30 × 30 m resolution (not shown) and are able to capture smaller patches of ecosystem service provision such as pocket parks and tree plantings, while the population projections are at the block group level; downscaled population data could provide a more fine-scaled analysis addressing the needs of programs providing parks and tree plantings.

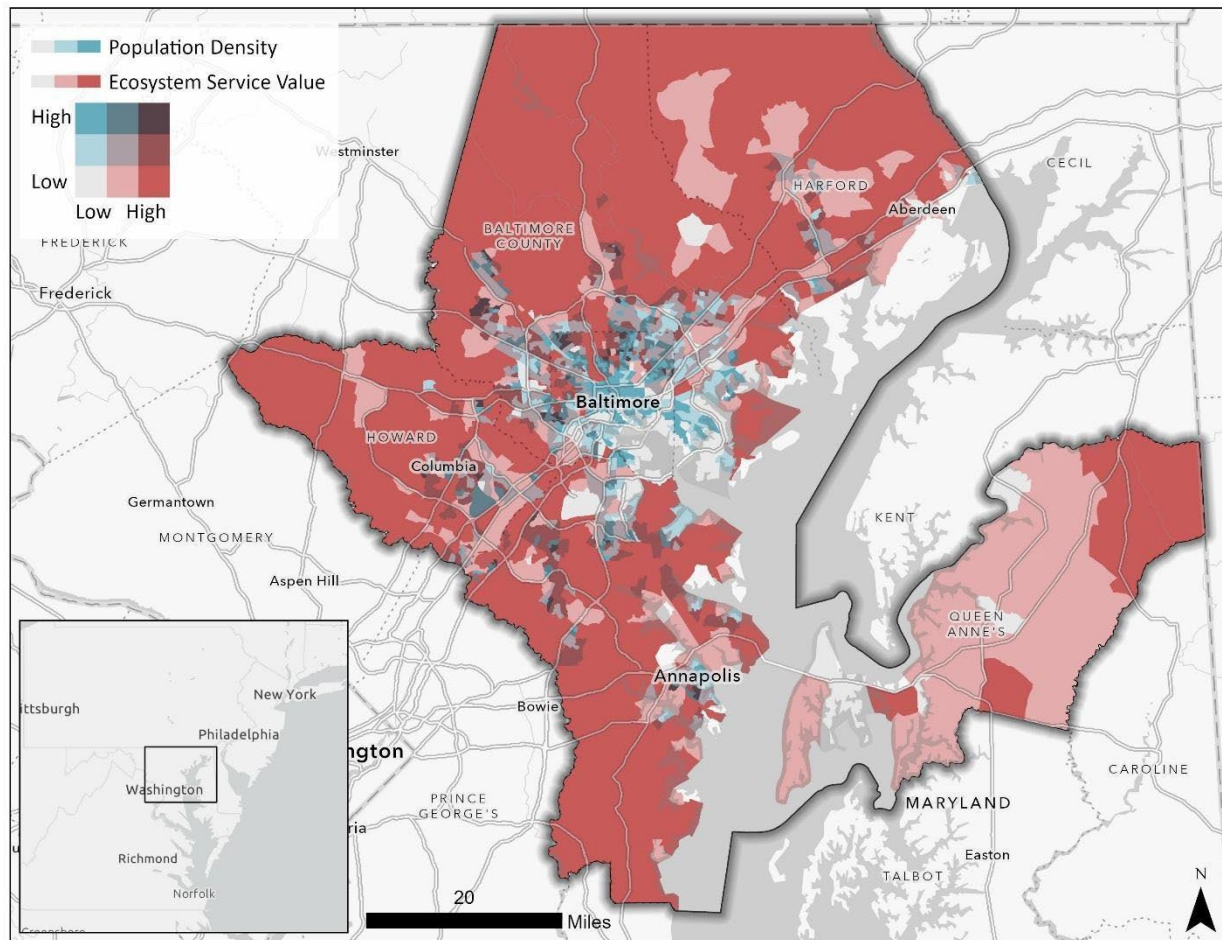


Figure 44. Projected population density in 2050 and current ecosystem service value bivariate choropleth.

Figure 44 closely mirrors the comparison of urban heat and ecosystem service values in Figure 45 with the exception of the northwest strip. The relationship between ecosystem service values and urban heat is bi-directional in that green spaces can ameliorate heat intensity but may also suffer from extreme heat events that cause plant stress (Gunawardena et al., 2017). There are several block groups in the outer suburban areas with both high urban heat and ecosystem service values, where there may be a decrease in ecosystem services due to repeated heat stress in the future damaging the ecosystems providing the value. Areas with high urban heat and low ecosystem service values, in turn, might benefit from participating in one of the urban tree planting or gardening programs should the soil resources be available for such a planting. Past successful examples of tree plantings in urban environments abound; however, care should be taken as climate stressors, local climate variability, and extreme heat can impact the success of these efforts (Ettinger et al., 2024; Li et al., 2024).

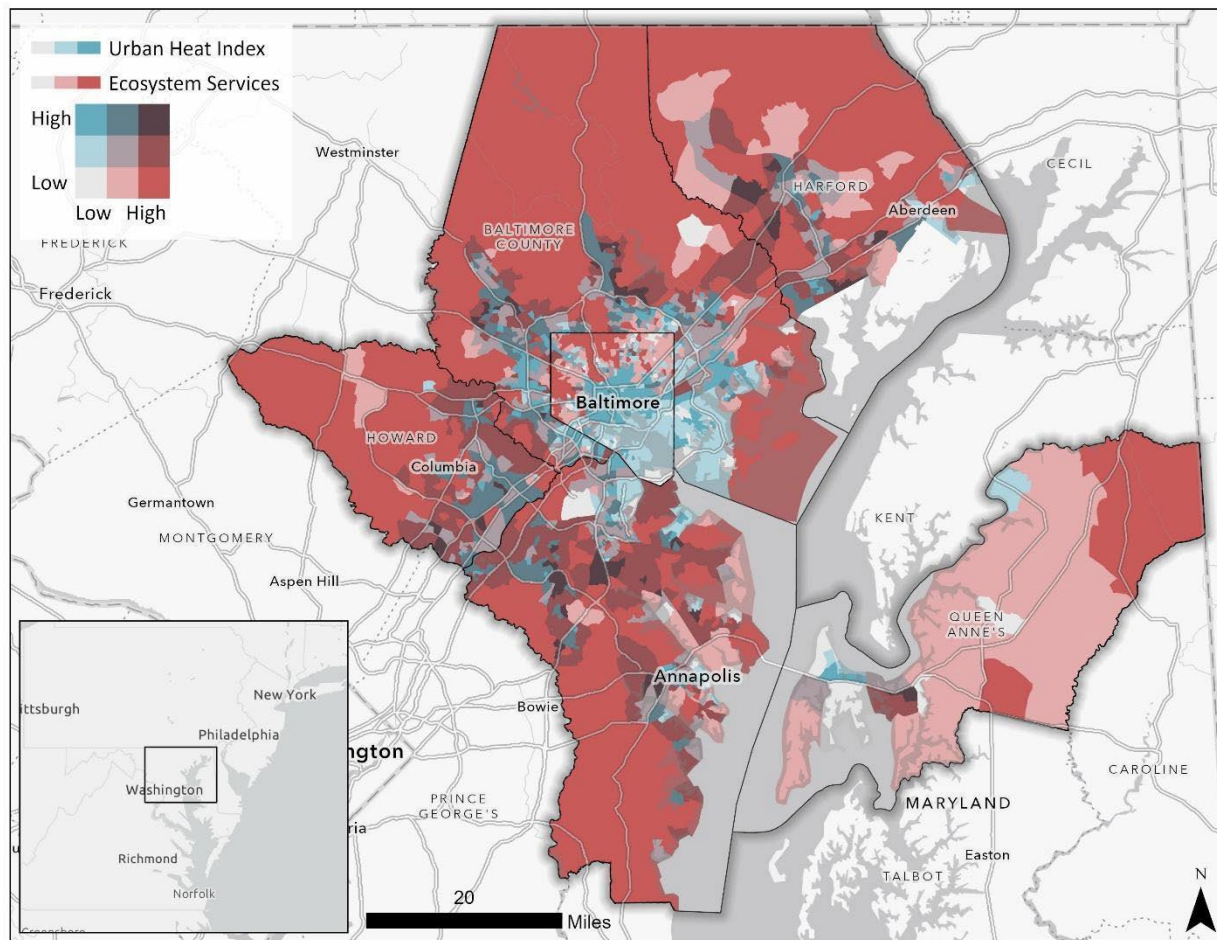


Figure 45. Urban heat and ecosystem service values.

3.1.3 Storm Surge and Structural Indicators

The structural exposure index is best interpreted with reference to individual indicators, since the exact location can make a large difference in flood risk and depth. These exposures, largely along the waterfront of both the Bay and tributary rivers, are most obvious when displayed against storm surge depth, which can inundate an area in a short amount of time. Management guidance recommends planning for Category 4 storm surges. This section highlights structures identified as important by the Resiliency Workgroup workshop that fall within the storm surge zone.

3.1.3.1 Shoreline Height Related to Storm Surge

This decision criterion highlights engineering limits of shoreline structures relative to predicted Category 4 storm surge height. The shoreline heights are from the Maryland Shoreline Inventory (Barbosa et al., 2004), which categorizes shoreline heights into four brackets: 0-5 ft, 5-10 ft, 10-30 ft, and over 30 ft. For this analysis, the maximum height was assumed within each bracket, allowing a best-case scenario within each bracket. Then, shorelines likely to be overtopped by storm surge were highlighted by calculating where the

maximum shoreline height is less than the nearest neighboring storm surge values (as calculated using the Near tool in ArcGIS Pro 3.4, and shown in dark blue in Figure 46). Aside from a few low-lying shorelines near Bowley's Quarters in Baltimore County, the majority of insufficient shorelines are found in Anne Arundel County. Moreover, a majority of Anne Arundel County's shorelines fall below the predicted storm surge levels. The likelihood of exceedance is tied to the probability of a Category 4 storm in the region, and storm intensity is expected to increase in the future due to warming water temperatures (NOAA Meteorological Development Laboratory, 2025).

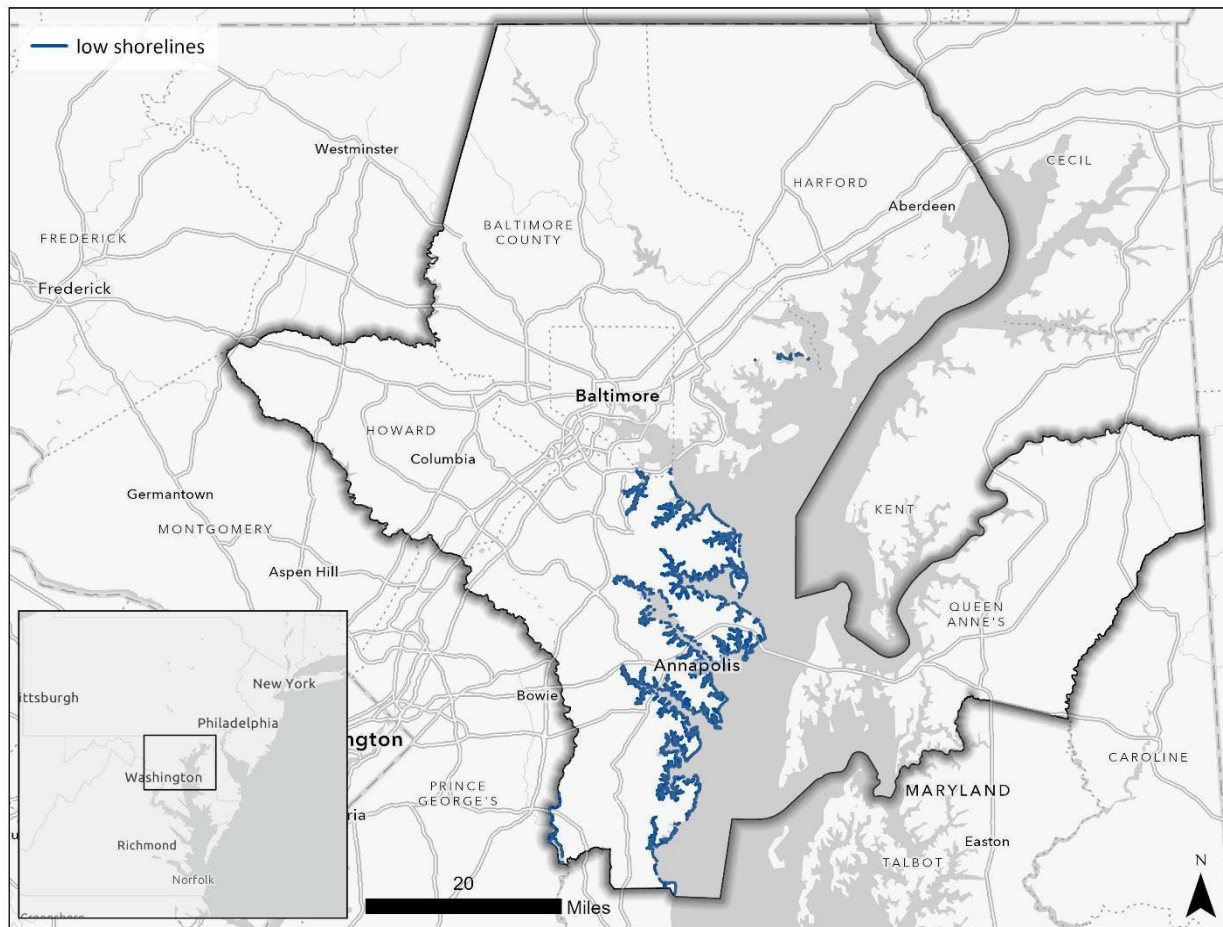


Figure 46. Shoreline height distribution below predicted Category 4 storm surge across the study area.

The differences observed between counties may be due to variations in local policies, development patterns, and ownership types (private vs. commercial). These factors likely encourage the use of hardened shorelines along the more industrialized waterfronts of Baltimore City and County, while Anne Arundel County may favor natural shorelines. If these natural shorelines (especially those containing oysters) remain intact, they could potentially adapt to rising waters through growth or retreat, offering more flexible protection compared to hard infrastructure like seawalls (Ridge et al., 2015). The question then becomes whether oysters can grow fast enough to keep up with sea level rise, and if the oysters or marsh grasses have a higher elevation place to migrate to if sea levels exceed their maximum depth.

While much of Baltimore's rivers are commercially occupied, Anne Arundel County's rivers are primarily residential. Certain neighborhoods in Anne Arundel County may face greater challenges in funding shoreline repair and maintenance if a storm overtops their shoreline protection, due to varied economic dynamics throughout the county's geography. Shoreline conditions, noted in the Shoreline Inventory but not depicted in the map, also vary, with some shorelines experiencing erosion or undercutting, leaving them vulnerable to collapse. Most constructed shorelines were installed or updated after Hurricane Irene in 2003 (Barbosa et al., 2004). As a result, regular maintenance is needed across the region, with particular priority for areas at greater risk of future flooding. Regular maintenance might involve rebuilding or supplementing sections of shoreline, adding height to shoreline where needed, or replanting nature-based infrastructure to better meet changing environmental conditions.

3.1.3.2 Critical Roads Related to Storm Surge

Highways serve as the primary mode of transportation in the area. Because of the region's extensive waterways, these highways include numerous bridges and segments that pass through low-lying areas. These low-lying areas are likely to be overtopped or washed out during storm events, and storm events are predicted to increase in intensity and frequency in the future due to warming water temperatures (NOAA Meteorological Development Laboratory, 2025). Since road heights are not included in any of the available road datasets for the state, it is difficult to determine exact road exposure (e.g., the road may be elevated above existing topography and therefore out of vulnerable low-elevation areas). Due to this unavailable data, roads are assumed to be at land level in Figure 51 and therefore flooded when adjacent land is flooded. However, note that bridges and wet areas are also often convergence zones, where transit between two areas relies on a single pathway. The landing areas around these bridges have been identified by Army Corps of Engineers as a major infrastructure concern in the city of Baltimore and the transit systems connected to it (U.S. Army Corps of Engineers, 2022). The recent collapse of the Francis Scott Key Bridge made clear how the loss of key convergence zones can greatly impact neighboring communities and travel time in the whole region (Mehta, 2024). Another bridge of special importance is the Chesapeake Bay Bridge, which has landings on both sides of the Bay in areas highly vulnerable to flooding (see Figure 47).

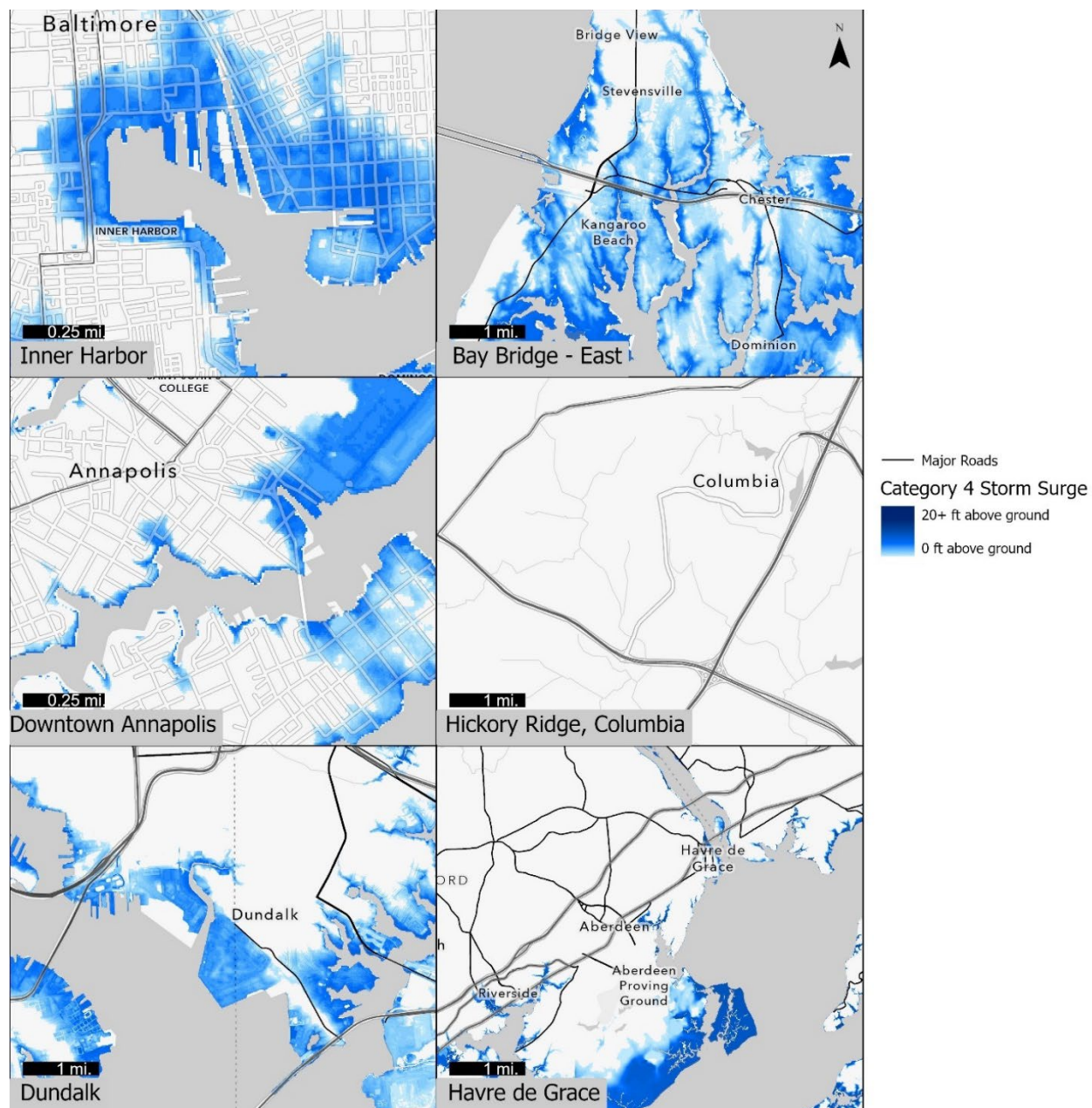


Figure 47. Major roads (those classified as primary or secondary) as related to storm surge predictions.

3.1.3.3 Stormwater Pipes Related to Storm Surge

Stormwater systems are built to collect runoff and convey it through channels or pipes to the Bay. While a few areas have engineered more complex systems, including stormwater retention ponds to decrease flow rates and diversions through wastewater treatment systems to remove chemical contaminants, the fundamental piping system design remains the same. During storm surge in low-lying areas, rising water from the Bay can reverse the flow of stormwater systems, forcing water back through the pipes and out onto the streets through manholes, rather than discharging at the usual outfalls into the Bay (see Figure 48 for a visual) (Sadler et al., 2020). This means that in storm surge-prone areas with combined sewer outfall systems, stormwater pipes can serve as a health risk as well as critical infrastructure, depending on which way the water is flowing (Volpitta, 2020).



Figure 48. Backflow from a manhole in Baltimore. Credit: Blue Water Baltimore.

Areas highlighted in the focus area map (Figure 49) show which stormwater pipes along the coast are susceptible to this dynamic by having elevations lower than the expected flood levels. Some (but not all) districts also keep track of pipe dimensions, quality, and materials, all of which affect flow rate, so more detailed stormwater studies in neighborhoods where these data are available can be helpful in addressing stormwater capacity issues. Combined sewer outfall systems, which pose a distinct health risk, are being phased out across the state but still exist and are relied upon in times of high stormwater flow, especially in historic and rural areas such as Havre de Grace. Given these site-specific details, neighborhoods identified through a visualization like the one shown in Figure 49 should consider their future risk and prioritize upgrades accordingly.

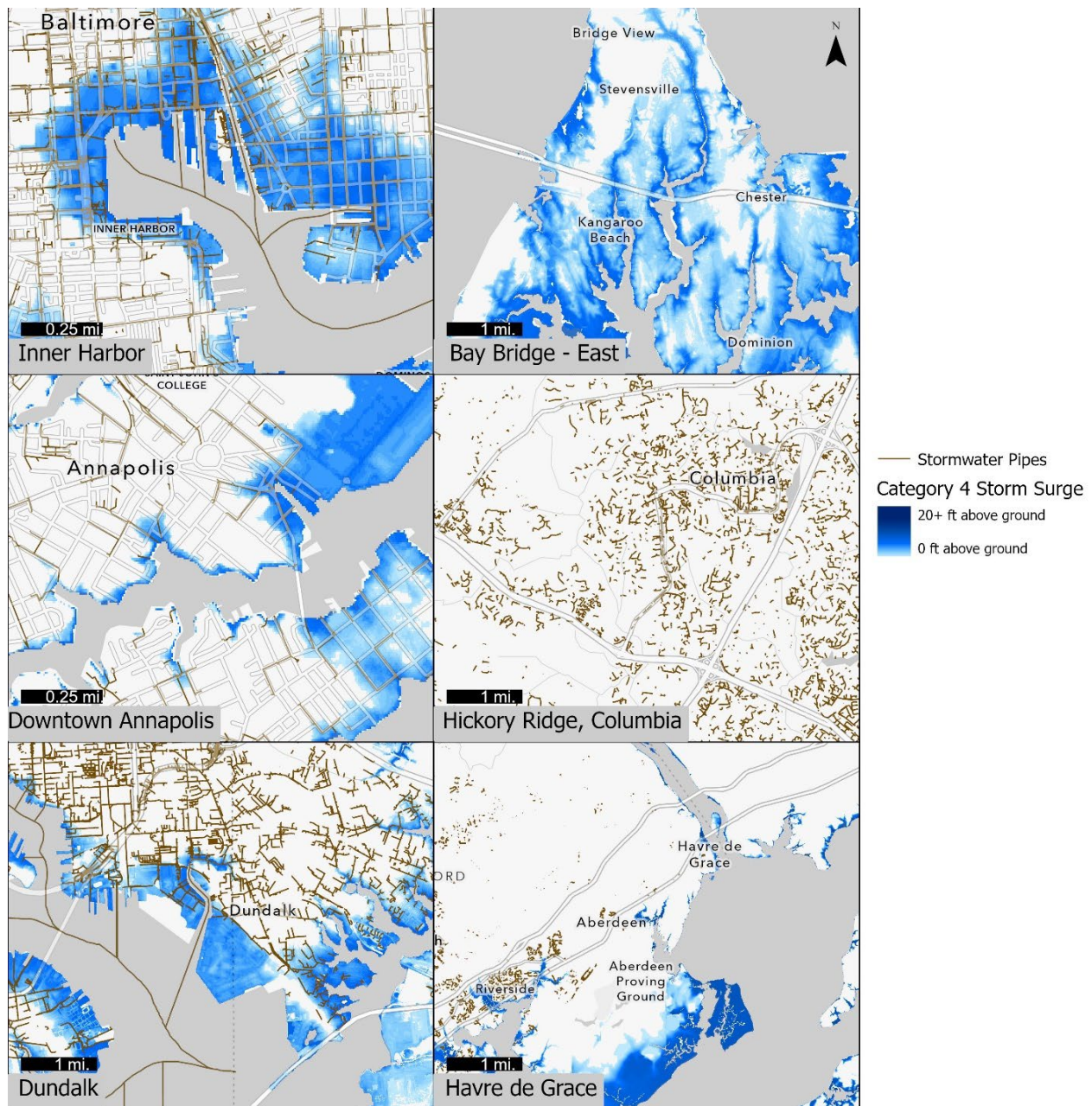


Figure 49. Piping displayed over blue tones indicate portions of the stormwater system where backflow can occur during storm surge events.

3.1.3 Combined Flooding

Stormwater flooding tends to settle in flat areas that collect runoff from throughout the watershed, while flooding from the Bay in the form of storm surge and sea level rise causes inundation from the waterfront upward into the watershed. Although this study did not analyze fully compounded flood hazards (see section 2.4.4), bivariate choropleth maps illustrate combined pressures from concurrent stormwater flooding and storm surge (Figure 50) as well as stormwater flooding and sea level rise (Figure 51). The highest-risk zones for concurrent flooding are waterfront zones where riverine deltas meet areas at high risk of sea level rise or storm surge. These include the areas around Essex, tributaries of the Patuxent, and the mouth of the South River. These high-risk zones are most at risk when the risk timing is synchronized, for example, an intense storm with winds pushing water onto the shore during high tide; these worst-case scenario situations would benefit from future scenario modeling.

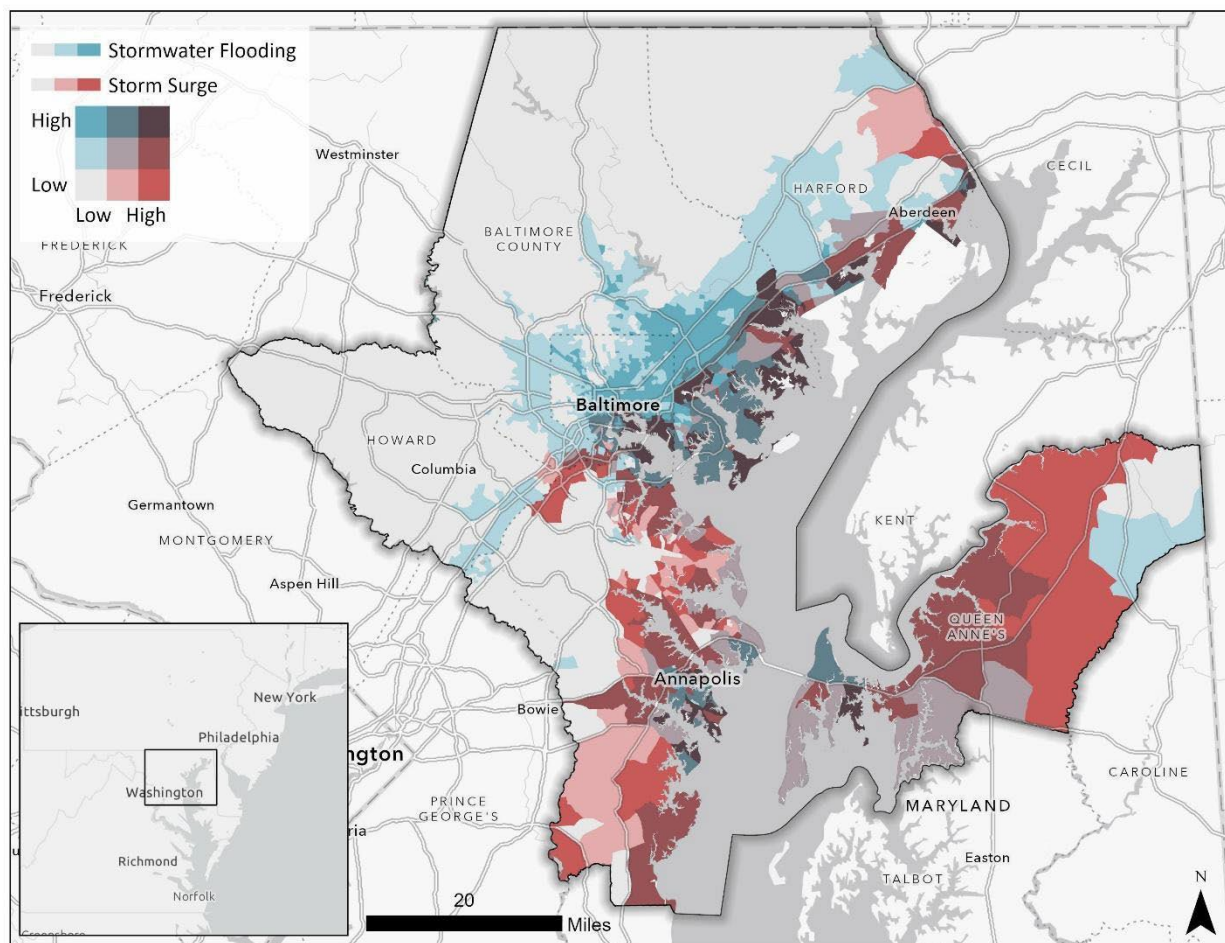


Figure 50. Block groups with co-occurring flooding threats from both stormwater and storm surge.

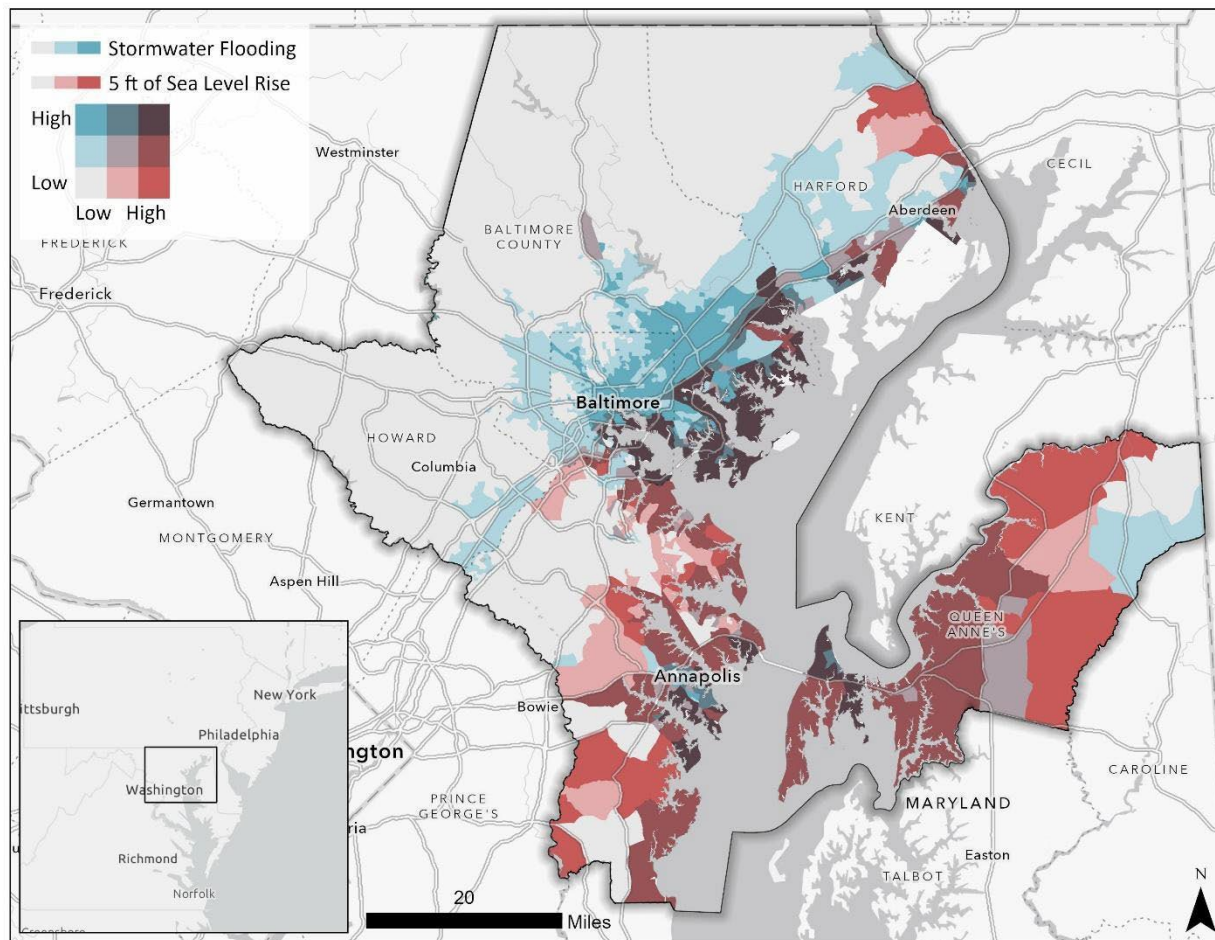


Figure 51. Block groups with co-occurring flooding threats from both stormwater and sea level rise.

3.2 Protective Benefits of Nature-Based Infrastructure to Community Resources

Shoreline protection provided by nature-based infrastructure was the top priority identified in the research prioritization exercise with project partners. However, since nature-based infrastructure is usually implemented at the property scale, the region-wide bivariate choropleth analysis is less applicable here. Instead, this section focuses on community resources from this assessment's structural exposure index, which were also identified as a key concern during the research planning process. The first part of this section investigates the proximity of natural infrastructure to key community resources; the second focuses on the shoreline neighborhood portion of the study area; the third investigates where gray infrastructure fits into the geography since it is the most common type of shoreline protection and competing choice for natural infrastructure in shoreline protection.

Additional structural data for this section was included for the maritime waters immediately adjacent to the study zone. These data were focused on oysters and included oyster plantings (2000 to Present) (Maryland

Department of Natural Resources, 2024a), natural oyster bars (Maryland Department of Natural Resources, 2022), oyster leases (Maryland Department of Natural Resources, 2024a), historic oyster bottom (Maryland Department of Natural Resources, 1977), and historic oyster plantings (Maryland Department of Natural Resources, 2023).

For this study, community resources are defined as sites of historical, social, or cultural significance to local communities. These include arts and entertainment districts (Maryland Department of Business and Economic Development, 2017), places of worship (ESRI, 2020), historic places (derived from the Maryland Inventory and National Register, with duplicates removed) (National Park Service, 2017; Planning, 2020), and protected areas listed in the Protected Areas Database of the United States (USGS, 2024b). These sites were selected because they reflect locations critical to local heritage and culture that face risks from environmental change.

3.2.1 Natural Infrastructure Proximity to Community Resources

This section examines the spatial relationship between natural infrastructure and community resources, assessing how natural infrastructure, such as wetlands and oyster reefs, provides possible protection benefits from changing environmental conditions and coastal erosion (Figure 52).

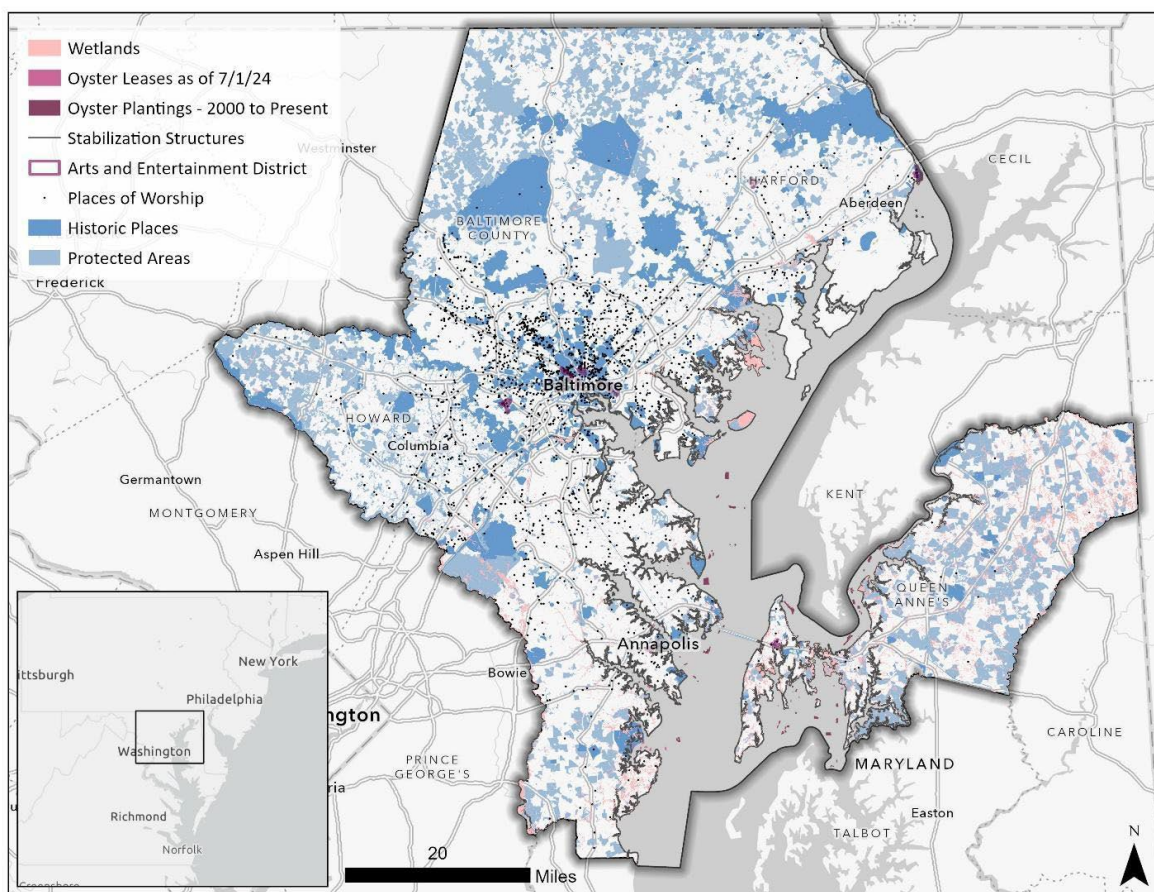


Figure 52. Spatial distribution of community resources and natural infrastructure.

The locations identified in this analysis support land use planning by identifying areas where natural infrastructure could reduce risks to community sites. Wetlands and oyster reefs can attenuate storm surge and mitigate flood risks, offering a natural defense against coastal hazards (Morris et al., 2018; Narayan et al., 2017). Compared to gray infrastructure, such as seawalls and levees, these nature-based solutions are often more sustainable and cost-effective in the long term (Narayan et al., 2016; Temmerman et al., 2013). However, wetlands and oyster reefs near urban areas face additional pressures from stormwater runoff and other pollutants, which can reduce their effectiveness (Birch and Rochford, 2010) and should be accounted for in future site-specific studies.



Credit: Henry Sage (University of Maryland)

3.2.2 The Coastal Buffer

To focus on properties near the water, a 0.5-mile buffer was applied to the shoreline inventory and wetland edges (from the structural index). Baltimore City planners also use a 0.5-mile buffer in their planning documents to measure which buildings and businesses may experience the benefits of natural spaces (City of Baltimore Department of Planning, 2018). Community resources within this buffer were then used in this analysis as a subset of the total study area most affected by shoreline dynamics.

Anne Arundel County contains the highest overall concentration of community resources within the coastal buffer (Figure 45). For natural forms of community resources, Queen Anne's County contains the highest percentage of protected areas, many of which are wetlands. It also has the highest concentration of oysters, which is the focus of many

restoration programs in the area (see Figure 1 for jurisdictional boundaries). The concentration of community assets near the coast, combined with the length of shoreline in each county, highlights both the scale of exposure and the need to evaluate where natural protections still exist as well as where they're missing.

Oysters as a form of green infrastructure have declined with the total oyster population over the last century. As shown in Figure 53, the top displays historic oyster data (Yates Bars³), including historic oyster bottoms and plantings, alongside historic places both color coded by whether they fall in the coastal buffer. In contrast, the bottom focuses on current oyster-related infrastructure, such as oyster leases and oyster plantings; this highlights the ongoing protection provided by natural infrastructure today and current management efforts. Viewed together, these maps reveal the extent of oyster coverage in the past and

³ Yates Bars were legally defined oyster bars based on local knowledge and codified by CC. Yates in the early 20th century. More information can be found here: <https://dnr.maryland.gov/fisheries/pages/oysters/historic-oyster-bottom.aspx>

highlight significant losses in natural infrastructure over time. Despite the consistent locations of historic places, the protective capacity of natural infrastructure has diminished due to the reduction of oyster habitats (currently less than 4% of historical extent and 2% of historical population).

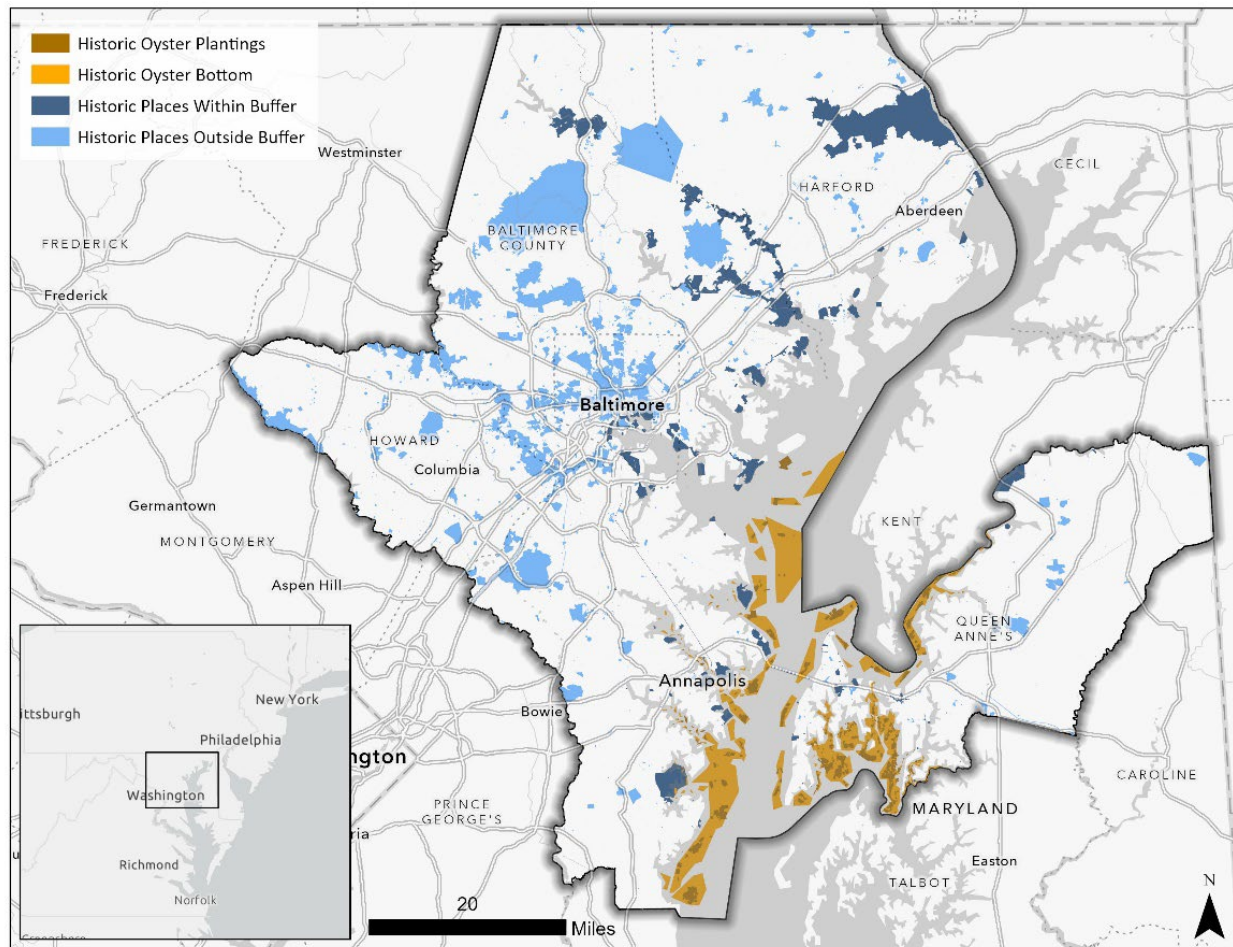


Figure 53. Comparison of past (top) and present (bottom) oyster reef coverage, highlighting differences in potential coastal protection for historic sites on a shoreline.

A range of shoreline protection types create a patchwork approach to shoreline management. Direct shoreline treatments are the most effective because they are tailored to site conditions, though offshore treatments and nearby natural areas also provide protection. Studies on the efficacy of shoreline treatments are unresolved as to what distances are critical but tend to focus on the 200–300 m adjacent to the shoreline (La Peyre et al., 2015; Vaidya et al., 2015; Vona et al., 2020). This distance should be directly measured for site-specific projects. Due to uncertain distances in the literature, Table 5 shows what kind of shoreline protection is closest to each type of community resource within the shoreline neighborhood and the average distance of that protection from the resource. For example, two thirds of arts and entertainment districts are protected by wetlands directly on their shoreline (zero m away), while the other one third are protected by gray structures also directly on their shoreline. Oysters are not the nearest shoreline in most

cases but are often paired with gray or wetland infrastructure in nearby shallow water. This is a trend that historically was very important and is likely to increase in prevalence with restoration efforts in the future (see Figure 53). The majority (65%) of community resources are currently protected primarily by wetlands. This information can be used to help community planners recognize the respective roles of natural and gray infrastructure and the impact those shorelines may have on community resource experiences (e.g., the viewshed from a historic estate).

Table 5. Community resources protected by natural infrastructure type.

Community Resource (from Structural Exposure Index)	Oysters Are Nearest Shoreline Type		Wetlands Are Nearest Shoreline Type		Gray Infrastructure Is Nearest Shoreline Type	
	Percent	Average Distance (m)	Percent	Average Distance (m)	Percent	Average Distance (m)
Arts and Entertainment Districts	0	N/A	67%	0	33%	0
Places of Worship	0	N/A	73%	96	27%	124
Historic Places	0.1%	52	47%	136	53%	92
Protected Areas	0	N/A	74%	31	26%	24

3.2.3 Contrasting Between Gray and Nature-Based Infrastructure

This section examines the spatial relationship between oyster leases, wetland restoration, and gray infrastructure in coastal protection efforts and how the type of infrastructure may vary depending on restoration funding source. Figure 54 illustrates the shorelines associated with key neighborhoods. In Maryland, oyster leases are primarily commercial aquaculture operations, with a record harvest of 94,286 bushels of oysters in 2023 (Maryland Department of Natural Resources, 2024c). While these leases are not designed for shoreline protection, they may contribute to wave attenuation, particularly when shell or spat-on-shell is planted near shorelines (NOAA Fisheries, 2022). They can either take the place of gray infrastructure, as seen around the Bay Bridge East panel of Figure 54, or be part of hybrid infrastructure installments, as observed around downtown Annapolis.

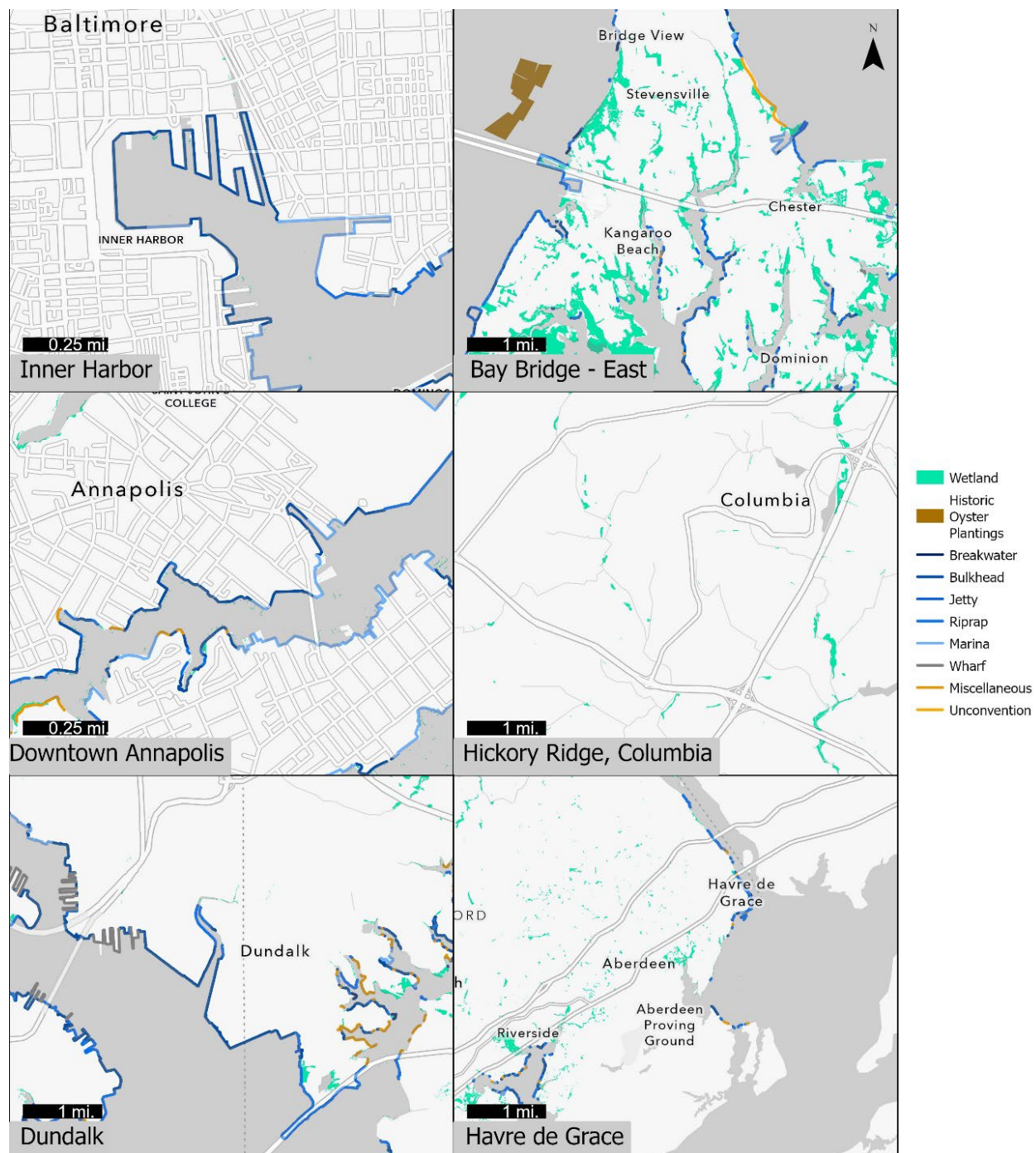


Figure 54. Distribution of oysters and shoreline stabilization by type across key waterfront zones in the study area.

The type of infrastructure also varies by funding source and motives for installing the shoreline. Oyster planting efforts are largely driven by restoration and industry replenishment initiatives led by organizations such as the Maryland Department of Natural Resources, the Oyster Recovery Partnership, NOAA, the U.S. Army Corps of Engineers, and the Horn Point Laboratory (Campbell, 2024). These efforts aim to enhance water quality through oyster filtration, improve marine habitats, and support Maryland's seafood industry.

Wetland restoration and maintenance in Maryland involve collaboration among organizations such as The Nature Conservancy, Ducks Unlimited, U.S. Fish and Wildlife Service, Maryland Department of Natural Resources and the USDA's Natural Resource Conservation Service (The Nature Conservancy, n.d.). Their initiatives focus on improving water quality, restoring habitats, and mitigating shoreline erosion, with funding from sources such as the Chesapeake and Atlantic Coastal Bays Trust Fund, the Waterway Improvement Fund, NOAA, and EPA's Chesapeake Bay Program (Maryland Department of Natural Resources, 2021). Wetland restoration projects also enhance biodiversity, increase resilience to changing environmental conditions, and support local economies through recreation and ecotourism (Maryland Department of Natural Resources, 2021).

Gray infrastructure, including seawalls, bulkheads, and breakwaters, is typically constructed by local governments and developers. Projects like the Atlantic Coast of Maryland Shoreline Protection Project, led by the U.S. Army Corps of Engineers and Maryland DRN and scheduled to begin in late 2025, aim to mitigate coastal erosion, flooding, and storm surges (U.S. Army Corps of Engineers and Maryland Department of Transportation, 2024). While gray infrastructure offers immediate protection for coastal developments, there is an increasing recognition of the benefits of integrating gray and natural approaches to balance structural defense with environmental sustainability (International Water Management Institute, 2024; NOAA Office for Coastal Management, 2025).

3.3.2.4 Community Resources Related to Sea Level Rise

Key community landmarks are often found in the forecasted flood zones, especially in historic districts built for boat transit like in the study region. A single flood event, such as Hurricane Isabel in 2003, can damage these resources beyond repair and leave lasting economic impacts for decades if not longer (Li et al., 2020). The slow approach of water from sea level rise is a similar threat, though differs in intensity and the certainty of occurrence. Figure 55 highlights parcels that contain community resources (a subset of the structural exposure index) within the study area that are at risk from a projected 2 ft of sea level rise, which is the projection for 2050, and what many communities are planning for currently. These parcels are administrative boundaries and may be noncontiguous.

This represents 14.6% of all community resources within half a mile of the shoreline at risk of sea level rise flooding by 2050. These priority properties may require adaptation measures by 2050 to protect their resources. Adaptation efforts might include lifting historic buildings, ensuring valuable property in these buildings is lifted off the floor, archiving infrastructure for future weather extremes, and other plans that combine climate adaptation and historic preservation (National Park Service, n.d.). Whether the potential loss of 14.6% of community resources in the waterfront areas is enough to shift cultural identity or economic activities is an empirical question. Comparisons between cities facing similar hazards may be helpful in predicting thresholds and avoiding crossing them.

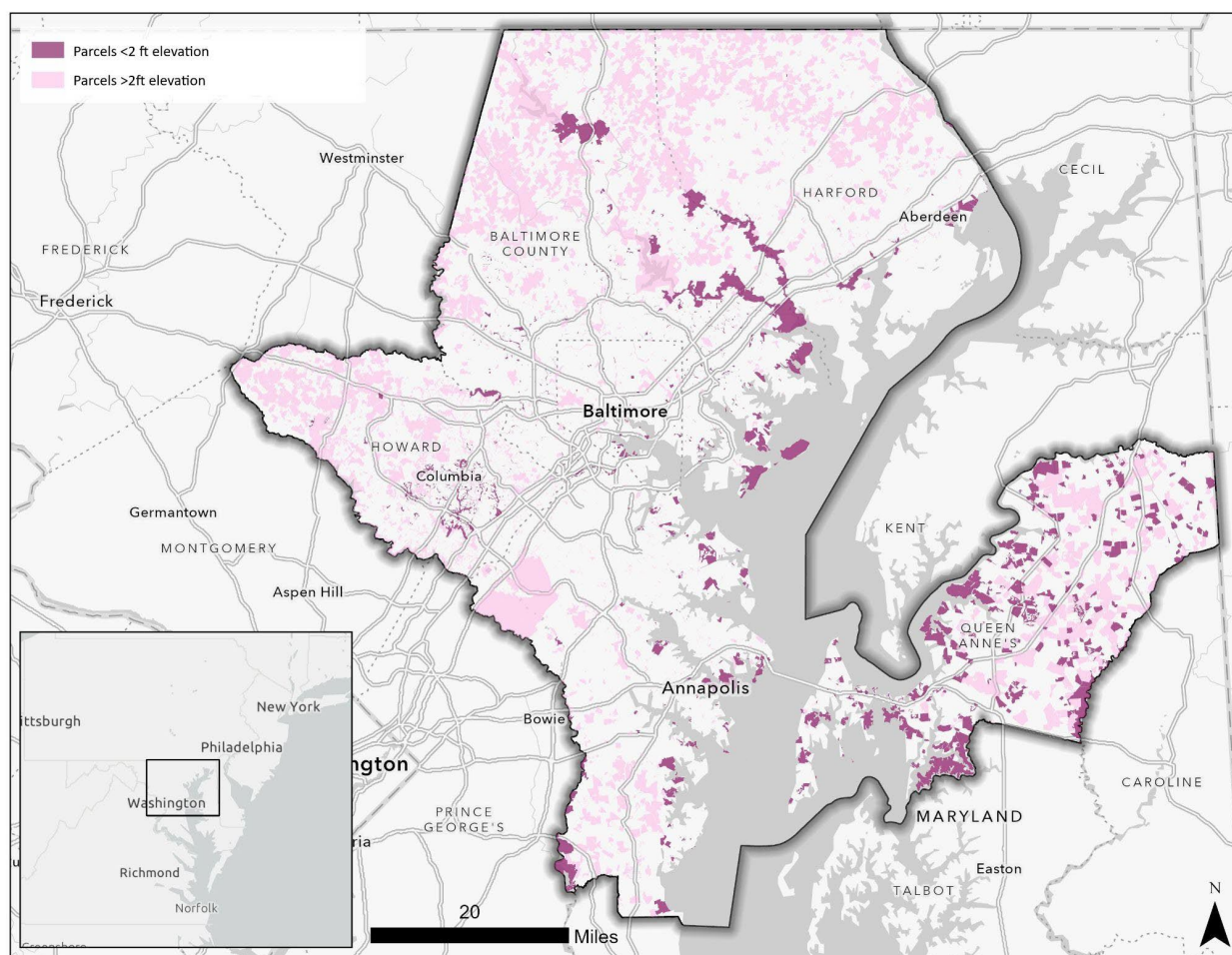


Figure 55. Property parcels of community resources at elevations less than 2 ft. Note, the property area of the community resource may be only partially affected.

Part 4: Conclusions and Applications

This report is intended to serve as a foundation for climate planning and mitigation efforts. It highlights vulnerability, exposure, and hazard co-occurrence across physical geographies and may therefore inform holistic adaptation efforts. Documentation of these components and where they overlap (risk) can also help identify areas dealing with multiple stressors. This type of foundational work is increasingly required by funding programs to qualify for adaptation grants, and hopefully this report can serve as a helpful reference for groups actively applying for such programs, as well as for education and outreach about handling multiple climate risks simultaneously.

The comparison of historic and current oyster extent protecting historical and cultural buildings is one example serving as a reminder of the effects of human development and activities in the area. Many of the programs that have adapted to changing environmental conditions and built shoreline protection fall under the “restoration” category of efforts since they are restoring historic ecosystem services. The value of the ecosystem services was likely much higher in the past across the whole study area, and historical benchmarks provide motivation to protect what services remain and rebuild where possible to face new challenges.

For the Chesapeake specifically, planning for the Watershed Agreement for Beyond 2025 is actively underway. The report guiding formulation of the new agreement—A Comprehensive Evaluation of System Response—identifies scientific needs and opportunities for future agreements and specifically highlights opportunities of nearshore environments throughout the Bay to provide climate resilience. It identifies one of the main needs of future work as targeted restoration areas rather than relying solely on voluntary action (Beyond 2025 Steering Committee, 2024). This risk assessment can support Beyond 2025 by helping identify targeted restoration areas including multiple criteria for prioritization and can also inform future work focused on cascading and compounding effects of changing environmental conditions.

4.1 Key Findings From the Data

While one key message of this assessment is to investigate the multitude of contributing factors to climate-driven risk in a community, there are also some key findings from subsets of that larger data collection that emerged from stakeholder feedback over the course of this project. The first focuses on stormwater flooding, which is a newer consideration in climate risk in the region and one receiving higher research attention as a result. Stormwater flooding is a threat not only due to the destructive potential of flowing stormwater but also in areas where it pools. By incorporating stormwater into an overall assessment of flooding risk, the focus shifts from the shoreline to the watershed, where stormwater can accumulate and flow through developments, causing damage and potentially delivering polluted water to the Bay.

The other hazard in the area with rising research attention is urban heat. Urban heat has historically risen in the study area, driven by the concentration of impervious, heat-absorbing surfaces such as asphalt and concrete, which create heat islands in urban areas and affect local communities. Baltimore’s history and past planning practices have resulted in neighborhoods with limited tree cover and green space. These impacts are disproportionately felt across the study geography, highlighting an opportunity for local mitigation efforts.

The intersection of hazard and vulnerability is especially important on individual properties that are owned by or have value for the community as a whole. Given the historic nature of both Baltimore and Annapolis, a large proportion of commercial and cultural landmarks are located along the waterfront, placing them in the risk zone for sea level rise and storm surge. These pieces of critical infrastructure serve areas throughout the study region, so the structural inventory presented here includes not only the infrastructure itself but also the transportation routes that connect to it.

In interpreting climate risk, the range of values is often presented as “low” to “high” relative to the values present in the study area. However, data ranges can be considered in terms of decision criteria, where certain values in the range have increased meaning. Calculating these criteria should be approached with cultural sensitivity and may be best left to the discretion of individual communities. Key examples are provided to initiate discussions with communities, such as where the height of existing shoreline infrastructure is below projected sea level rise or where extended periods above 90°F may threaten public health and ecosystem services.

4.2 Future Applications

While this assessment provides a foundational collection of data, perhaps one of the most useful results is the research wish list created by contributors to this assessment (Appendix B). For the three of these desired questions focused on thresholds especially, this assessment provided some groundwork on how to sensitively discuss and research thresholds but was capable of addressing only a handful of examples of where thresholds have already been calculated. These examples rely on existing policy recommendations and documented decision criteria. Future work could empirically measure the threshold where the system state changed, likely by tracking indicators over time rather than as a snapshot like this assessment.

Since this study is based necessarily on secondary data, there are limitations based on what is available. This is especially true for data layers used to identify community resources, which rely on government registries of physical locations of historical, cultural, or artistic value. This means that resources not visible to government entities or those with non-exact locations (e.g., valuing access to cultural foods such as blue crab) are not included. A more comprehensive analysis would require additional datasets and direct community engagement. Further collaboration with stakeholders, such as outlined in section 1.2.3, is necessary to refine this assessment and ensure its relevance to resilience planning. Future research should expand on these findings to ensure that resilience strategies effectively integrate both community heritage and environmental sustainability.

This assessment is a snapshot in time with the best available data at this time. However, the many concepts covered in this assessment conceptualize time differently—for example, climate estimates tend to look to 2050 and 2100, mortgages for real estate are on a typical 30-year time horizon, and population estimates beyond density are difficult to predict more than a year out. However, there is desire in the community to comprehensively discuss future conditions, or project all the components of this assessment out to climate time scales. For some, like urban heat and stormwater, research is already underway to get closer to this goal, while others will require new methodologies entirely. In addition, climate models are available in increasingly high resolution, while population data are restricted to census geographies; finding a spatial scale for integrating these data types in those future conditions would be helpful to adaptation and mitigation planners.

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Appendix A: Glossary

Adaptation: The process of adjusting to new climate conditions in order to reduce risks to valued assets (U.S. Climate Resilience Toolkit, 2021).

Adaptive Capacity: The ability of a person, asset, or system to adjust to a hazard, take advantage of new opportunities, or cope with change (U.S. Climate Resilience Toolkit, 2021).

Bivariate Choropleth Mapping: A mapping technique that displays two variables within the same map and map legend, utilizing graduated color symbols.

Climate: Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system (Intergovernmental Panel on Climate Change, 2023).

Changing Environmental Conditions: Changes in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Changing environmental conditions may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. (Intergovernmental Panel on Climate Change, 2023).

Community Resources: Locations or sites of historical, social, or cultural significance to local communities, including arts and entertainment districts, places of worship, historic places, and protected areas.

Component: A key concept used to represent one aspect of risk. Depending on context, these are sometimes composite indicators or models, used to quantify large concepts as one value.

Critical Infrastructure: Essential systems and assets that are vital to a community's security, economy, public health, and safety.

Exposure: The presence of people, assets, and ecosystems in places where they could be adversely affected by hazards (U.S. Climate Resilience Toolkit, 2021).

Extreme heat: The occurrence of abnormally and uncomfortably hot weather conditions (adapted from Intergovernmental Panel on Climate Change, 2023).

Flood: The overflowing of the normal confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged. Floods can be caused by unusually heavy rain, for example, during storms and cyclones. Floods include river (fluvial) floods, flash floods, urban floods, rain (pluvial) floods, sewer floods, coastal floods, and glacial lake outburst floods (Intergovernmental Panel on Climate Change, 2023).

Coastal flooding: Floods that occur as a result of sea level rise, above-normal high tides, wave-driven run up, storm surge, and other coastal and ocean dynamics (e.g., El Niño–Southern Oscillation, North Atlantic Oscillation).

Stormwater flooding: Floods that occur as a result of rainwater.

Riverine flooding: Floods that occur along riverways as a result of river overflows.

Hazard: An event or condition that may cause injury, illness, or death to people or damage to assets (U.S. Climate Resilience Toolkit), including loss of property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources (Intergovernmental Panel on Climate Change, 2023). Hazard profiles may incorporate location, extent, previous occurrences, likelihood, and/or future probability.

Impacts: The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial (Intergovernmental Panel on Climate Change, 2023).

Index: A method of aggregating numerous individual indicators into one quantitative value.

Indicator: A specific data source that contributes to a component.

Mitigation: Sustained action that can reduce or eliminate risk to people and property from hazards and their effects (Federal Emergency Management Agency, 2024).

Resilience: The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (Freitag et al., 2024).

Risk: The potential for negative consequences where something of value is at stake. In the context of the assessment of climate impacts, the term “risk” is often used to refer to the potential for adverse consequences of a climate-related hazard (U.S. Climate Resilience Toolkit, 2021). In this program, risk is estimated by intersecting vulnerability with hazard probability.

Sea Level Rise: An increase in the height of sea level, both globally and locally (relative sea level change) at seasonal, annual, or longer time scales due to: (i) a change in ocean volume as a result of a change in the mass of water in the ocean (e.g., due to melt of glaciers and ice sheets), (ii) changes in ocean volume as a result of changes in ocean water density (e.g., expansion under warmer conditions), (iii) changes in the shape of the ocean basins and changes in the Earth’s gravitational and rotational fields, and (iv) local subsidence or uplift of the land (Intergovernmental Panel on Climate Change, 2023).

Storm Surge: The abnormal rise of water generated by a storm, over and above the normal astronomical tide, expressed in terms of height above predicted or expected tide levels (NOAA Meteorological Development Laboratory, 2025).

Sensitivity: The degree to which a system, population, or resource is or might be affected by hazards (U.S. Climate Resilience Toolkit, 2021). In this program, sensitivity is estimated by intersecting exposure with hazard probability.

Stakeholder: Local partners of project partners whose interests may be positively or negatively affected as a result of project execution or outcomes.

Urban Heat Island Effect: Heat islands are urban areas that experience significantly higher temperatures than surrounding rural regions. Man-made structures like buildings, roads, and other infrastructure absorb and re-emit more solar heat compared to natural landscapes such as forests and bodies of water (Heaviside et al., 2017).

Appendix B: Research Wish List

These questions were collected through a series of conversations with resilience practitioners in Maryland. They are in no particular order, and some were mentioned more than others. They are organized by broad categories and summarized from often much-more-detailed thoughts.

Governance Questions:

- Legislative geographic landscape: What is possible? Where and what incentives are on the ground guiding people's decisions currently?
- Figure out how to connect state-level data and programs to people in charge of the built environment systematically.
- Can we flag or forecast when and where communities need to prioritize climate adaptation or face big consequences?
- How does zoning need to change in order to match where the humans will be?
- Impacts of natural infrastructure and restoration efforts, especially economic.

Retreat + Migration Questions:

- Are there identifiable tipping points or thresholds at which different decisions should be made, like retreat?
- Is infrastructure moving alongside the people, climate, or both?
- Spatially resolute shoreline mapping data and how they are expected to perform in future climate scenarios.

Better Population Data:

- Downscaled population data, with a goal of addressing needs and dynamics of minority and water-dependent communities, and economic effects.
- Forecasting human patterns out to the same length of time as climate models (and this matches up with planning efforts).
- Heritage and stories of the community: How to get them on the map, especially as people move.
- Are the information needs or tipping points different for water-dependent industries? Or commercial risk in general?
- What are the impacts on the tax base if people choose retreat?
- If there is a community that is less wealthy, their infrastructure is likely valued less but might be just as important—how do we count that?

Better Risk Assessments:

- How do changing environmental conditions affect access to water?
- Can we map out conditions that might help a community create a menu of adaptation options? To advise communities if what they're considering is enough to meet the forecasted risks.
- Contaminants as a risk, and how that overlaps with restoration efforts.
- Forecasting marsh migration (and where there might not be space for that to occur).
- Ecosystem service approach to valuation (e.g., not all green space provides the same benefits).

Other:

- Vulnerability verification: How do communities identified as vulnerable do after an actual storm event, and how do people in that place perceive their vulnerability?

Appendix C: Data Inventory

Component	Indicator	Data Source	Date	Title
Population Projections	population	https://gisdata.baltometro.org/datasets/BMC::round-10-cooperative-forecast/about	7/18/2022	BMC Cooperative Forecast
	population	https://www.epa.gov/gcx/iclus-downloads	5/22/2020	ICLUS Version 2.1.1
Structural	schools	https://gii.dhs.gov/gii/apps/sites/#/hifld/	12/7/2022	HIFLD K-12 Public Schools from DOE
		https://gii.dhs.gov/gii/apps/sites/#/hifld/	5/27/2022	HIFLD K-12 Private Schools from DOE
	places of worship	https://gii.dhs.gov/gii/apps/sites/#/hifld/	7/1/2020	HIFLD from IRS master files
	emergency shelters	https://gii.dhs.gov/gii/apps/sites/#/hifld/	7/3/2023	HIFLD from FEMA and Red Cross
	farms/food suppliers	https://www.chesapeakeconservancy.org/projects/cbp-land-use-land-cover-data-project	2018	Chesapeake Conservancy 1-m LULC, agricultural designations
	wastewater infrastructure	https://www.arcgis.com/home/item.html?id=0895b107f9184e7cb31707767b506a64%2F1000	6/15/23	EPA FRS through Living Atlas
	shoreline protection	https://www.arcgis.com/home/item.html?id=73af68c10ebd459086b4a2cb8c69f550	8/27/2019	MSI - Stabilization Structures
	Bay access points	https://data.imap.maryland.gov/datasets/maryland::maryland-shoreline-inventory-access-structures/about	8/27/2019	MSI - Access Structures
	hospitals	https://gii.dhs.gov/gii/apps/sites/#/hifld/	9/20/23	HIFLD Hospitals
	police stations	https://gii.dhs.gov/gii/apps/sites/#/hifld/	2/2/2021	HIFLD Local Law Enforcement Locations
	fire stations	https://gii.dhs.gov/gii/apps/sites/#/hifld/	3/12/2024	HIFLD Fire and EMS Stations
	colleges	https://gii.dhs.gov/gii/apps/sites/#/hifld/	12/10/2022	HIFLD Colleges and University Campuses
	government facilities	https://gii.dhs.gov/gii/apps/sites/#/hifld/	10/19/2021	HIFLD Major State Government Buildings
	banks	https://gii.dhs.gov/gii/apps/sites/#/hifld/	5/17/2022	HIFLD FDIC insured banks

Component	Indicator	Data Source	Date	Title
	grocery stores	https://archive.data.jhu.edu/dataset.xhtml?persistentId=doi:10.7281/T1/QUDBC6	2022	Maryland Food System Map (JHU)
	hardware stores	ArcGIS Business Analyst (see SST layers)	2023	ArcGIS Business Analyst by NAICS 44414 - Hardware retailers
	gas stations	ArcGIS Business Analyst (see SST layers)	2023	ArcGIS Business Analyst by NAICS 4571* service stations
	electric vehicle chargers	https://www.arcgis.com/home/item.html?id=ae69915223264806bbaad36f43543757	9/15/2023	MD EV Charging Stations
	electrical cooperatives/producers	https://gii.dhs.gov/gii/apps/sites/#/hifld/	9/21/2023	HIFLD Power Plants
	drinking water treatment facilities	https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/200	6/7/24	SDWIS (EPA)
	critical roadways	https://catalog.data.gov/dataset/tiger-line-shapefile-2023-state-maryland-primary-and-secondary-roads	2017	Census TIGER primary and secondary road classifications
	hazardous waste facilities	https://services.arcgis.com/cJ9YHowT8TU7DUyn/arcgis/rest/services/FRS_INTERESTS_RCRA_TSD/FeatureServer	live (clipped 6/7/24)	Federal Registry Service (EPA) - RCRA treatment, storage, and disposal
	public transit lines	https://data.imap.maryland.gov/datasets/maryland::maryland-transit-baltimore-metro-subway-lines/about	3/1/24	MTA subway lines
		https://data.imap.maryland.gov/datasets/maryland::maryland-transit-mta-bus-lines-1/about	3/7/24	MTA bus lines
		https://data.imap.maryland.gov/datasets/maryland::maryland-transit-light-rail-stations/about	3/1/24	Light Rail Stations
	stormwater infrastructure	Requested directly from county GIS staff	2024	
Ecosystem Service Value	ecosystem services	https://data.imap.maryland.gov/maps/maryland::maryland-ecosystem-services-total-ecosystem-service-economic-value-dollars-per-year/about	8/27/19	
Stormwater	flow accumulation	https://data.usgs.gov/datacatalog/data/USGS:77ae0551-c61e-4979-aedd-d797abdcde0e	2024	
	rainfall intensity	https://prism.oregonstate.edu/normals/	2024	

Component	Indicator	Data Source	Date	Title
	geologic soil group	https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo	2024	
	land use	https://planning.maryland.gov/Pages/OurProducts/DownloadFiles.aspx	2024	
	slope	same as flow accumulation above	2024	
	elevation	same as flow accumulation above	2024	
	distance to drainage networks	https://www.usgs.gov/national-hydrography/national-hydrography-dataset	2024	
Storm Surge	storm surge	https://www.nhc.noaa.gov/nationalsurge/	2024	SLOSH MOM
Sea Level Rise	sea level rise	https://coast.noaa.gov/slrdata/	2024	
Urban Heat	Landsat input data	https://landsat.gsfc.nasa.gov/satellites/land-sat-8/	2024	
	heat sensors	https://www.baltimoresustainability.org/urban-heat-island-sensors/	2024	
	land cover	https://coast.noaa.gov/digitalcoast/data/ccapregional.html	2024	
	normalized difference vegetation index	https://www.arcgis.com/apps/mapviewer/index.html?webmap=b93cf70452af447bab2b4fb570a10b56	2024	
	NOAA urban heat	https://www.noaa.gov/news/hot-days-in-city-it-s-all-about-location	2018	
	urban heat island severity	https://hub.arcgis.com/datasets/4f6d72903c9741a6a6ee6349f5393572/explore?location=39.218525%2C-75.981192%2C9.91	2019	
	global urban heat index	https://sedac.ciesin.columbia.edu/data/set/sdei-global-uhi-2013/data-download	2013	

Appendix D: Resilience Coordinator Network

Maryland Sea Grant observed that coordination is essential to working together toward a healthy and prospering Chesapeake Bay, yet connection among coordinators is informal, and support for coordinator needs is sporadic. Maryland Sea Grant invited people who identified as (or wanted to learn more about) coastal resilience coordinators to come together, share challenges they face, learn from one another on ways to overcome those challenges, and consider how best to interact in the future. The Connecting the Dots workshop occurred in person on August 14, 2024, at the University of Maryland Golf Course at College Park, Maryland. Forty-two participants across federal and state government, academia, and non-governmental organizations attended the workshop, mostly from Maryland (93%) and Virginia (5%) as well as Delaware (2%).

Read the full workshop report here:

https://www.mdsg.umd.edu/sites/default/files/2025-08/CoordinatorWS24_Report.pdf

The workshop aspired for the following outcomes:

- 1) The Chesapeake Bay coastal resilience community recognizes coordinator roles in information exchange and relationship building. They better support their associated needs to enact and maintain those responsibilities;
- 2) Coastal resilience-related coordinators' ability to effectively engage members/stakeholders and advance groups' resilience goals is improved;
- 3) Coordinators understand and strengthen the mosaic of different coastal climate groups working toward a healthy Chesapeake Bay and coastal zone. This effort helps demonstrate how information is transferred between individuals and shows whether the resulting networks could be strengthened through increased connections.

Methods

Workshop participants were asked to fill out three network analysis questions regarding different areas of coastal resilience. The questions were distributed prior to the workshop via a Qualtrics survey/worksheet as well as during a 30-minute work session with an on-paper worksheet in the first half of the in-person workshop (participants completed these questions once either on Qualtrics or in-person on paper). The worksheet collected their name and employer(s) and asked the following questions:

- a) Nature-based infrastructure and sea level rise: Who do you go to for information or advice on **nature-based and other conservation solutions** to sea level rise, and how often do you speak about nature-based and conservation solutions? *List four individuals' names, organizations, and how often on a scale of Annually (1), Monthly (2), Weekly (3), Every couple of days (4), or Daily (5).*
- b) Community perspectives and engagement: Who do you go to for information or advice on **community perspectives and engagement on coastal resilience**, and how often do you speak about community engagement? *List four individuals' names, organizations, and how often on a scale of Annually (1), Monthly (2), Weekly (3), Every couple of days (4), or Daily (5).*
- c) Monitoring coastal health: Who do you go to for information or advice on **monitoring coastal health in the Chesapeake Bay region**, and how often do you speak about monitoring? *List four individuals' name, organizations, and how often on a scale of Annually (1), Monthly (2), Weekly (3), Every couple of days (4), or Daily (5).*

Each question had a space for four possible answers, though instructions explained to workshop attendees that they did not have to fill out all four spaces. For each person listed, respondents were also asked to provide that person's organization and to rank the frequency of communication about the subject of the question on a scale of one to five. The scale was provided in the instructions: 1 = annually, 2 = monthly, 3 = weekly, 4 = every couple days, or 5 = daily.

Network diagrams were produced via the R statistical software using the igraph package (Csardi and Nepusz, 2006). During an afternoon session of the workshop (about an hour long), the network diagram for each subject matter was displayed on a projected slide, and workshop participants were broken into groups to discuss the networks. Workshop organizers circulated the room to answer questions and keep track of the main topic of conversation.

The groups were posed with the following prompts:

- What are some initial impressions (~5 minutes per map/20 minutes total)?
 - Who/what groups are missing from each map?
 - How can we improve connectivity on coastal resilience?
- In a space that has many players and is highly networked, what still does not function well? What needs improvement?
- In what ways can coordinators better connect and coordinate with one another?

Results

Four network diagrams can be created from the questions asked of workshop participants. The first three address particular aspects of adapting to changing environmental conditions that may require subject-matter expertise, and the fourth is all knowledge pathways combined. The first of these diagrams represents information flow about nature-based and other solutions to sea level rise. There are 22 statistical clusters, including one large cluster consisting of about one-third of the participants. Four people have positive betweenness scores, representing important connections between these clusters.

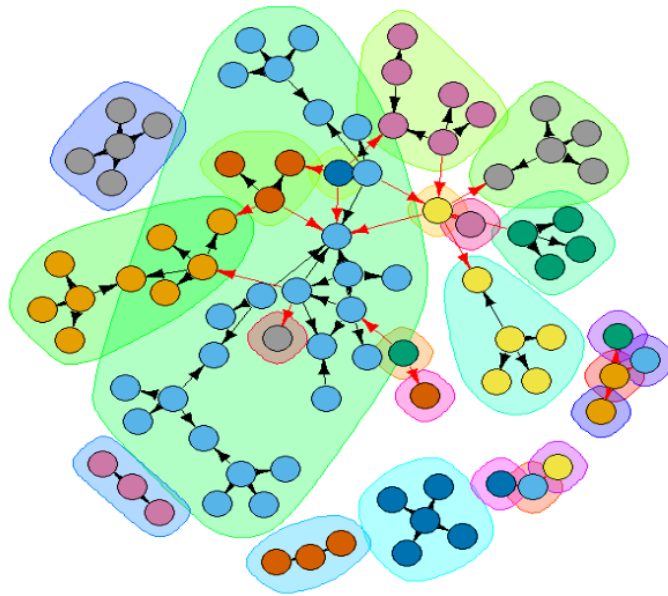


Figure D1. Network diagram for sharing information about nature-based and other solutions to sea level rise.

The second of these diagrams represents information flow about community perspectives and engagement. There are 16 statistical clusters, with one very large cluster containing over half of the participants. Five people have positive betweenness scores, representing important connections between these clusters. Of these, three are the same individuals serving this role in the nature-based and other solutions to sea level-rise network.

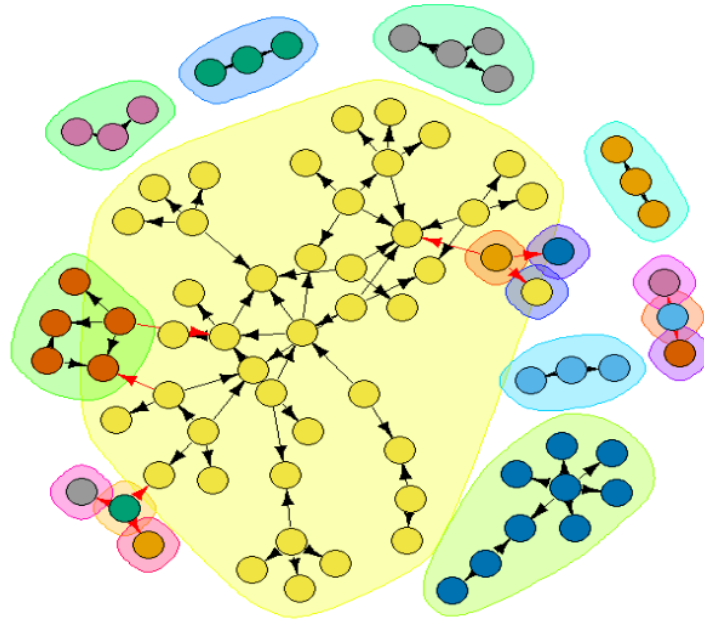


Figure D2. Network diagram for sharing information about community perspectives and engagement.

The third of these diagrams represents information flow about monitoring coastal health. There are 15 statistical clusters, with the largest cluster containing only about one-quarter of the participants. This is the most disconnected network of the three, something that participants quickly concluded upon viewing the network diagrams. There are six people with positive betweenness scores, representing important connections between these clusters. This includes two people who had not served this role for either of the previous subjects.

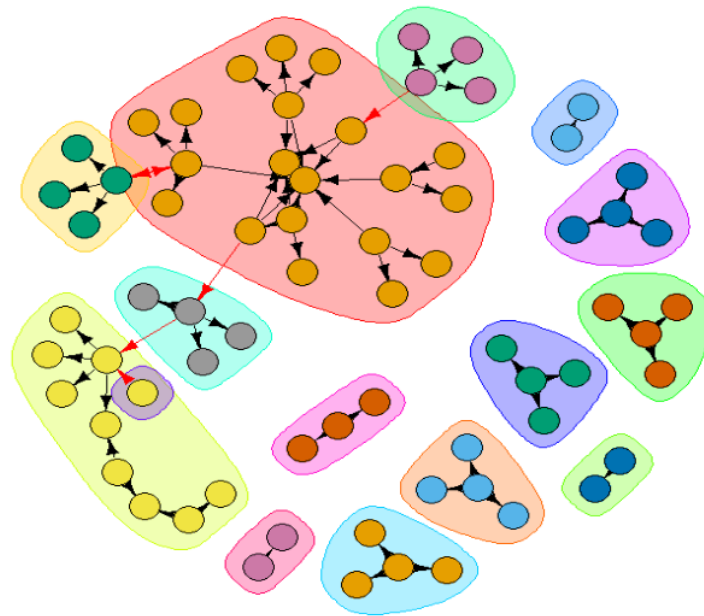


Figure D3. Network diagram for sharing information about monitoring coastal health.

When combined, all three show more of a condensed network, though there are still a few unconnected clusters and clusters reliant on ten positive-betweenness connecting individuals (adding four new individuals from subject-based networks). Visualizing the entire communication network, rather than separated by subject matter, allows different kinds of inquiry beyond network structure. For example, Figure D4 is color coded not by statistical clusters (of which there are many) but by the node's primary sector of employment. The groupings of people appear to typically include members from different sectors.

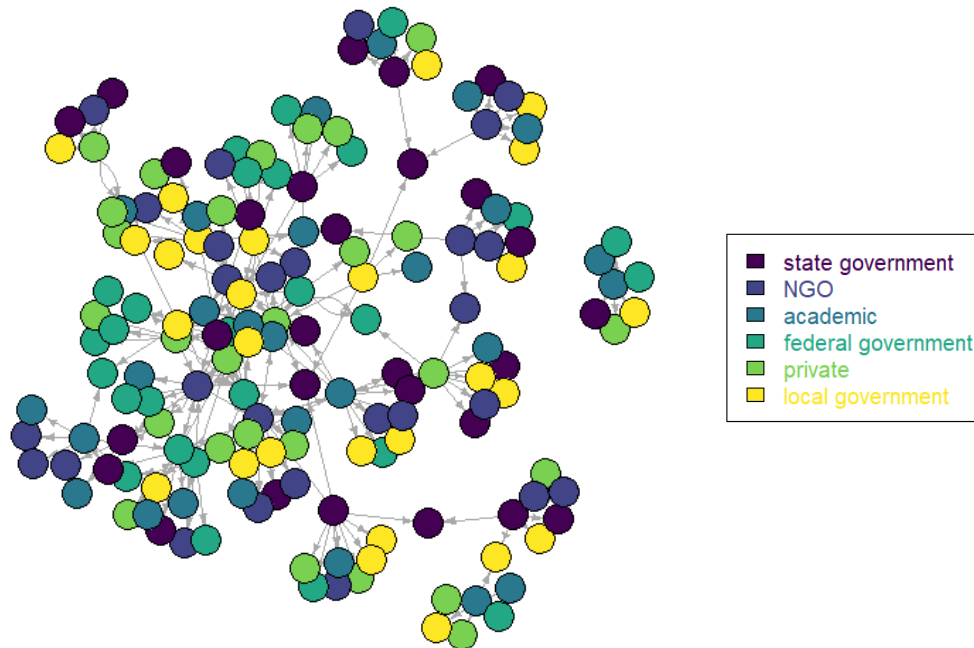


Figure D4. Network diagram of all information-sharing pathways. Nodes are color coded by their sector of employment. NGO = non-governmental organization.

Edge density for each of the subject-based networks is not significantly different and is, in many cases, very similar (0.012–0.013), as is degree centrality (1.85–2.05, $p=0.52$), eigenvalue centrality (0.101–0.124), and mean distance between nodes (1.4–1.5). So, while the details of each network might be different (e.g., who is playing the connector role), the structures of the three subject networks are not significantly different.

The discussion in the workshop after showing participants the subject-matter network diagrams focused on the following subjects:

- There were many questions about what's "right" or "should be."
- That the networks were generally disconnected, and monitoring seemed more disconnected than the others.
- What would happen if you combined all three?
- Are the small clusters all work colleagues leaning on each other, friend groups, or what?
- Trying to guess who the "hubs" were.
- Curiosity about where the transmitters are getting their information from.
- The role of gatekeepers and how to gain the benefits of those kinds of people without the drawbacks, and also some discussion of what happens when those people leave their position?
- Are these connections reliant on work teams or friendships?

Conclusions

One of the first questions one can ask of a network analysis is how well connected the members of a particular network are. In this case, there are independent clusters, especially when broken out by subject matter. As a whole, these clusters are slightly better connected primarily by relying on additional people serving as connectors (i.e., with high betweenness scores). This suggests a vulnerability in the network should one of these connectors remove themselves from the network by taking a new professional role, moving out of the area, or retiring. Conversely, this pattern also suggests the positive role a boundary-spanning organization can serve by providing professional responsibility for maintaining and building those important connections. If one were to measure this network in future years after a concerted effort to promote collaboration between resilience professionals, the effects could be measured by comparing a “before” and “after” network.

The reason this network analysis was structured around particular aspects of resilience was to test whether network structure varied by subject-matter expertise. Since resilience is a relatively new field that pulls both staff and theoretical foundations from a variety of fields, one might expect uneven network development between different aspects of resilience (Cutter, 2016). However, in this case, all three subject-based networks were structured similarly, suggesting that, for Maryland resilience professionals, at least, the expertise networks are structured the same. This may mean that they are at a similar level of development; this structural cause is likely given that many (if not most) of the resilience coordinator positions in the region are relatively new.

Individual key players varied a bit between subject networks, however, suggesting there is a role for subject-matter expertise specific to just one aspect of resilience. These key players include those serving critical connecting roles between groups, but also information aggregators (as depicted by many incoming edges). The workshop organizer plays both of these roles in all four social networks depicted, though that may be an artifact of having leveraged her social network to advertise the workshop. The information aggregation role in this case can serve to share and compare information about resilience, giving these individuals the best opportunity to identify best practices for resilience and shared narratives across subject matters and geographies.

As with most social networks, these are a measure of a snapshot in time, both in terms of the resilience professional field as it develops in Maryland and in terms of who was available and willing to attend the workshop. One of the goals of the workshop, and follow-up activities it inspired, was to connect resilience professionals throughout the state. Therefore, if these networks were re-created at a similar workshop in the coming years, it might be able to pick up on the effects of workshop networking. If the exercise were expanded to include others who did not attend the workshop, it would also potentially fill in some missing connections.

The questions underlying network creation also focused on information flow of all forms and its frequency but could, in the future, ask about the consistency of those connections. For example, are the connections through personal networks or formalized through professional responsibilities? One could also track information flow through the network to test if any important pathways are missing. For example, when this report is released, where does it enter the network and how does it spread? The networks presented here mark the beginning of the growth of an important professional network and will be both helpful in building that network and tracking effects of resilience funding programs in the region.

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