

Sea-Level Rise and Coastal Habitats of the Chesapeake Bay: A Summary

NATIONAL WILDLIFE FEDERATION

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Global warming is changing the face of the Chesapeake Bay by accelerating the rate of sea-level rise. At risk is an amazing diversity of coastal habitats, from sandy beaches and barrier islands along the Atlantic Coast to coastal marshes, swamps, seagrass beds, and estuarine beaches in the bay itself. Together, these habitats support thousands of species of fish and wildlife, and they are a linchpin for the regional economy, culture, and quality of life.¹ This short report summarizes results of a detailed modeling analysis commissioned by the National Wildlife Federation of how Chesapeake Bay habitats will be affected by sea-level rise in the coming century.

Coastal habitats in the Chesapeake Bay region will be dramatically altered if sea levels rise globally about two feet by the end of the century, which is at the low end of what is predicted if global warming pollution remains unaddressed. Over 167,000 acres of undeveloped dry land and about 161,000 acres of brackish marsh would be lost, replaced in part by over 266,000 acres (415.6 square miles) of newly open water and 50,000 acres of saltmarsh. Ocean and estuarine beaches also fare poorly, declining by 58 percent and 69 percent, respectively, by 2100. In addition, more than half of the region's important tidal swamp is at risk. Coupled with increasing human population and development pressures, losses of land to sea-level rise will put habitats at great risk unless proactive measures to protect vulnerable lands are put in place.²

Sea-level rise should be a major consideration in the region's coastal management and ecological restoration plans. It is particularly important that we (1) preserve the ability of habitats to migrate inland as sea levels rise by discouraging development in vulnerable areas and avoiding structures such as seawalls and bulkheads; (2) facilitate natural sediment buildup and artificial replenishment of sediments in coastal wetlands and beaches; and (3) improve the resiliency of fish and wildlife species by maintaining a diverse array of habitats. By identifying which specific locations and habitats in the bay region are especially vulnerable to sea-level rise, this summary and the accompanying technical report will be an important tool for informing the decisions of coastal resource managers and other officials.



CONFRONTING GLOBAL WARMING

Report



George Gentry, U.S. Fish and Wildlife Service (USFWS)

The Chesapeake Bay: A National Treasure

The Chesapeake Bay provides critical stopover and wintering habitat for more than one million migratory waterfowl, including the canvasback, mallard, redhead, American black duck, tundra swan, and Canada goose.³ The bay's coastal marshes are home to great blue heron, snowy egret, and other familiar birds, and they provide important food sources and nesting sites for numerous songbirds, mammals, reptiles, and amphibians. The region's beaches support some of the largest populations of shorebirds in the

western hemisphere such as red knot and piping plover, and are a critical nesting site for sea turtles.⁴ And, of course, the Chesapeake Bay sustains recreational and commercial fisheries worth billions of dollars annually, including popular blue crab, rockfish, menhaden, and eastern oyster.

Unfortunately, the region's coastal habitats and the ecological systems they support face serious problems due to human activities, including excess nutrient runoff into the bay, deforestation, over-fishing, invasive species such as nutria and mute



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swans, and wetland destruction from agricultural, urban, and suburban development.⁵ Numerous efforts are currently underway to restore the health of the Chesapeake Bay. While there have been several significant conservation successes, such as the return of rockfish and Canada goose populations to healthy numbers, the bay still faces many problems. Today, the task before us is even more daunting because we also face the challenges brought on by human-caused global warming.



Mary Hollinger, National Oceanic and Atmospheric Administration (NOAA)

Global Warming and Rising Seas: A Matter of Degrees

Scientists have widely and conclusively determined that global warming is happening and that burning fossil fuels is largely to blame.⁶ Global warming is already having an impact on the Chesapeake Bay.⁷ Left unchecked, global warming will mean higher average air and water temperatures, rising seas as

glaciers and ice caps melt, and more-extreme weather events such as floods, droughts, and heat waves.⁸ As a result, the region's coastal habitats and the fish and wildlife that depend on them are at great risk.

With its expansive coastline, low-lying topography, and growing coastal population, the Chesapeake Bay

region is among the places in the nation most vulnerable to sea-level rise. Many places along the bay have seen a one-foot increase in relative sea-level over the last century, half of which is attributed to global warming and the other half to naturally subsiding coastal lands—a factor that places the Chesapeake Bay region at particular risk.⁹ Already, many of the bay's coastal marshes and small islands have been inundated. At least 13 islands in the bay have disappeared entirely, and many more are at risk of being lost this century.¹⁰

With its expansive coastline, low-lying topography, and growing coastal population, the Chesapeake Bay region is among the places in the nation most vulnerable to sea-level rise.

STUDY APPROACH

This report summarizes the results of an extensive analysis of sea-level rise impacts on coastal habitats along the Chesapeake Bay, Delaware Bay, and the ocean beaches of southern New Jersey, Delaware, Maryland, and Virginia.

The National Wildlife Federation commissioned Jonathan S. Clough of Warren Pinnacle Consulting, Inc., to apply the Sea Level Affecting Marshes Model (SLAMM, Version 5.0) to the Chesapeake Bay region. The SLAMM model is widely regarded as the premier research tool for simulating the dominant processes involved in wetland conversions and shoreline modifications during long-term sea-level rise. Our analysis looked at a range of sea-level rise scenarios from the 2001 Intergovernmental Panel on Climate Change assessment, ranging from a 12.2-inch rise to 27.2-inch rise by 2100 (presented here). We also modeled a rise of up to 2 meters (78.7 inches) by 2100 to accommodate for recent studies that suggest a significantly greater sea-level rise is possible during this century.¹¹ Results for the entire study region and all scenarios are available at www.nwf.org/sealevelrise.

Delaware Bay

Maryland Shore

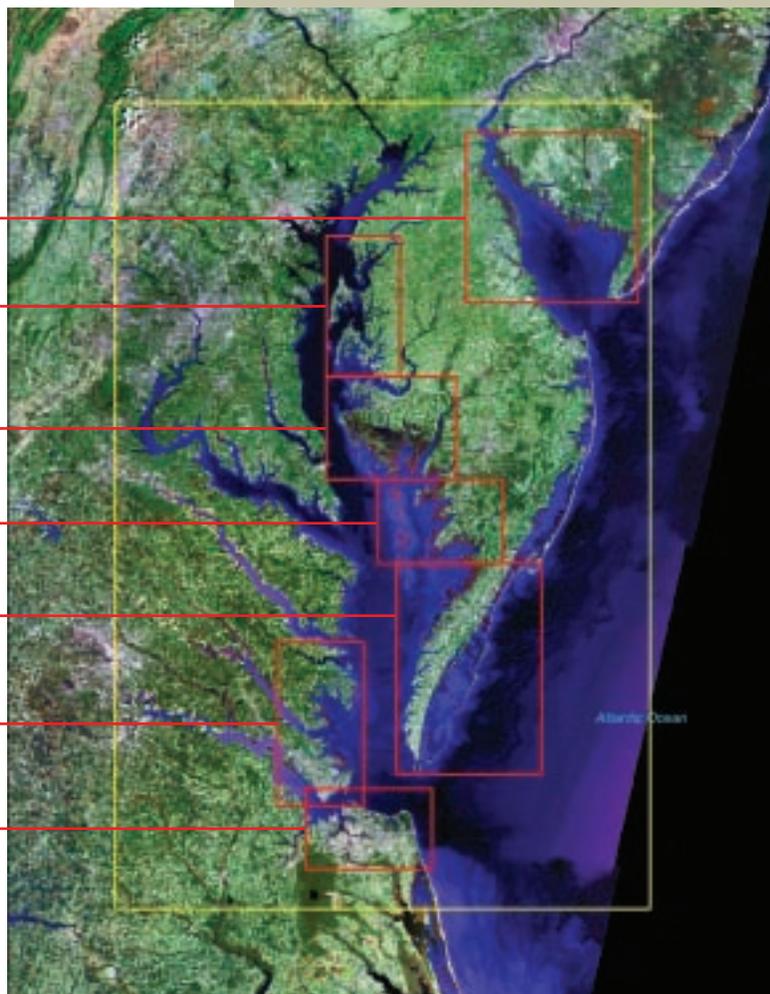
Blackwater National Wildlife Refuge

Tangier Sound

Virginia's Eastern Shore

Upper Tidewater Region

Lower Tidewater Region



Changing the Face of the Bay

A global sea-level rise of just over two feet will significantly reshape the coastal landscape of the Chesapeake Bay region. For example, coastal marshes would be inundated with salt water, converting 161,000 acres of brackish marsh and 29,000 acres of tidal swamp to less ecologically diverse saltmarsh or open water.¹² Many coastal plant and animal species are adapted to a certain level of salinity and tidal influence, so these shifts will make habitats more

favorable for some species, and less so for others.¹³

Over 167,000 acres of undeveloped dry land would be lost or replaced with wetlands. As dry land becomes saturated, the water table will increase, contributing to the expansion of open water inland. Furthermore, sea-level rise will make coastal and inland areas more susceptible to storm surges. The depth of water in estuaries has a significant influence on wave action during

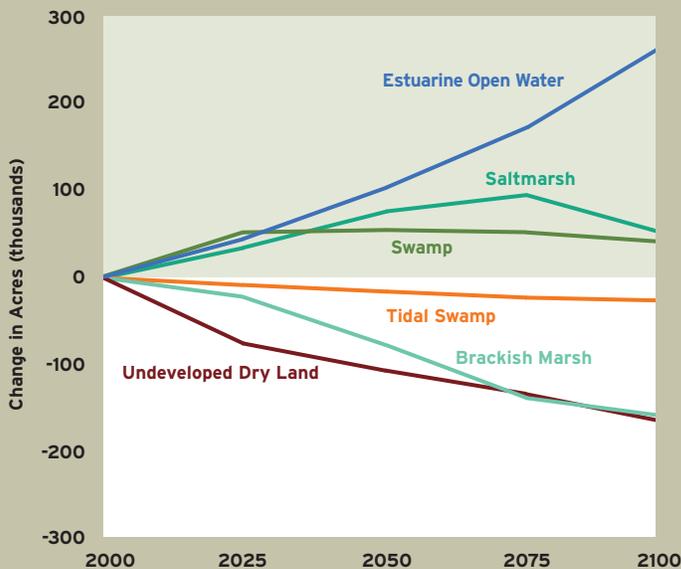


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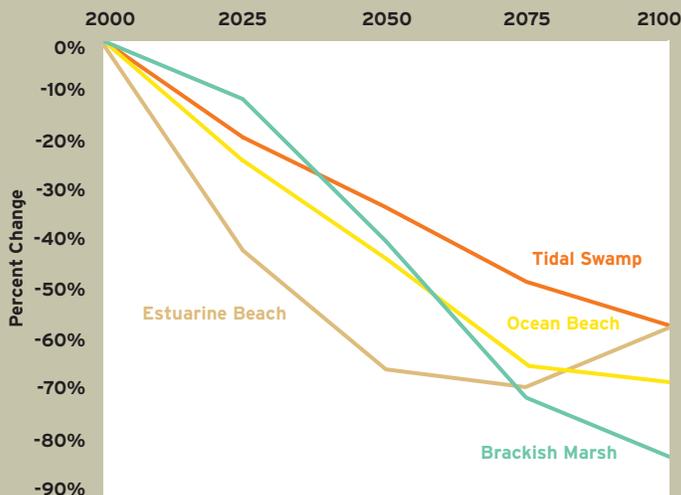
storms: the deeper the water, the larger and more destructive the waves.¹⁴

Ocean and estuarine beaches in the region also would experience widespread loss, declining by 58 percent and 69 percent, respectively, by 2100. Coastal armoring can further exacerbate beach erosion, by disrupting natural wave action that replenishes beaches. Ultimately, coastal communities could be relegated to continual beach re-nourishment projects using dredged materials to maintain beaches, a process that is not only costly but can be harmful to native fish and wildlife.

Coastal habitats such as marshes and beaches may be able to accommodate moderate changes in sea level by migrating inland, increasing elevation through the accumulation of sediments, or building up their own organic matter through decomposition of roots and leaves.¹⁵ Some river deltas along the western shore of the Chesapeake Bay, for example, have sufficient deposition of sediments for marshes to maintain constant elevation.¹⁶ As sea-level rise accelerates in the coming decades, however, the potential for coastal wetlands to naturally keep pace is likely to decline.¹⁷ Furthermore, the opportunity for inland migration of beaches and coastal wetlands is becoming increasingly reduced in parts of the Chesapeake Bay region due to coastal development and associated armoring by seawalls, dikes, and other structures.¹⁸



Habitat types in the Chesapeake Bay region projected to experience the largest changes in overall area due to a 27.2-inch increase in global sea level. Results are shown for the entire study area.



Habitat types in the Chesapeake Bay region projected to lose over 50 percent of their area by 2100 with a 27.2-inch rise in global sea level. Results are shown for the entire study area.

Treasured Places at Risk

Many favorite areas of the Chesapeake Bay where we go to fish, hunt for waterfowl, bird watch, and play on the beach will be affected if sea levels rise as predicted. The consequences for fish and wildlife will be far-reaching. Below we highlight some of the changes that we may see along the bay, noting that similar changes will be likely across the region.

Blackwater National Wildlife Refuge is a crown jewel among Chesapeake Bay's treasured places. Unfortunately, it could be largely underwater by 2100. Dramatic habitat

losses are predicted for the refuge and surrounding areas, where global sea-level rise is compounded by high rates of land subsidence due to groundwater withdrawal for agriculture¹⁹ and relatively lower rates of natural accretion in marshes.²⁰ The site is predicted to lose over 90 percent of its tidal fresh marsh, tidal swamp, and brackish marsh, which are converted to saltmarsh and, ultimately, open water. The loss of brackish marsh could be particularly harmful to species that have adapted to these habitats, including rockfish and white perch, as well as anadromous species such as herring and shad, which use brackish marsh habitat as they transition between their freshwater and saltwater life cycles.²¹ Similarly, the loss of tidal fresh marshes could affect minnows, carp, sunfish, crappie, and bass, which depend on these habitats for shelter, food, and spawning.²²

These losses from sea-level rise would come on top of habitat degradation in the Blackwater National Wildlife Refuge due to invasive species—in particular, nutria, whose feeding patterns have devegetated broad areas of marsh grasses, and mute swans, which are known to overgraze on the submerged aquatic vegetation favored by native waterfowl.

Tangier Sound is home to some of the bay's larger islands—including Smith, Deal, and Tangier—the majority of which could be gone by 2100. Towns on the main land, like Crisfield, will also see surrounding wetlands disappear and undeveloped dry land inundated by rising seas. Thousands of acres of brackish marsh in this region will be converted to salt marsh and open water, possibly ravaging lucrative commercial and recreational

COLOR KEY FOR ALL MAPS

Developed Dry Land	Transitional Saltmarsh
Undeveloped Dry Land	Saltmarsh
Swamp	Tidal Flat
Cypress Swamp	Inland Shore
Inland Freshwater Marsh	Rocky Intertidal
Tidal Swamp	Estuarine Beach
Tidal Freshwater Marsh	Ocean Beach
Brackish Marsh	Blackwater NWR



Blackwater National Wildlife Refuge: Initial Condition



Blackwater National Wildlife Refuge: Year 2100 (27.2 inches)



Tangier Sound: Initial Condition



Tangier Sound: Year 2100 (27.2 inches)

fisheries that depend on healthy marshes. The critical seagrass beds in this area are also at significant risk from sea-level rise and increased deposition of sediments from the Blackwater area to the north.²³

Virginia's Eastern Shore faces a dramatic loss of estuarine and ocean beaches. By 2025, estuarine beach is projected to decline by 52 percent and ocean beach by 26 percent. By 2100, over 80 percent of these beaches could disappear and be converted to open water. Like other regions around the



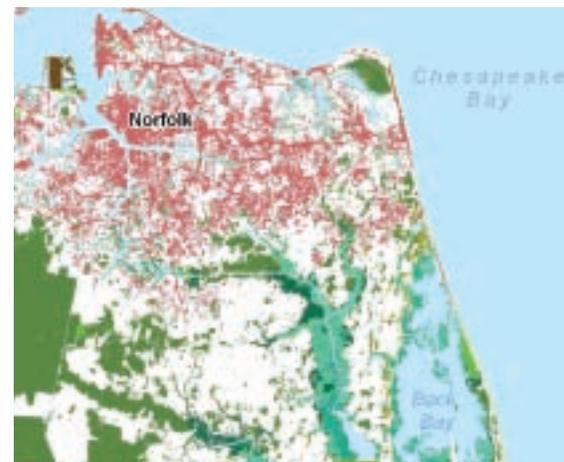
Virginia's Eastern Shore: Initial Condition



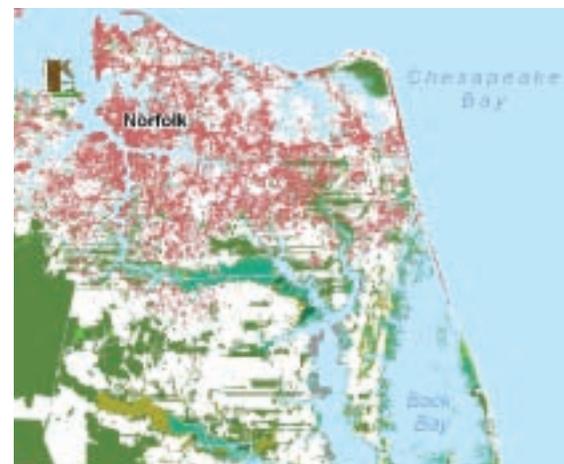
Virginia's Eastern Shore: Year 2100 (27.2 inches)

bay, the peninsula is projected to lose more than half of its brackish marsh by 2050, with a nearly complete loss by 2100. The extremely rare sea-level fens are also at risk. Located upland of wide, ocean-side tidal marshes on the upper east side of the peninsula, these habitats are comprised entirely of open, freshwater wetlands whose primary water source is groundwater.²⁴ Only certain types of plants and animals can thrive there, including ten-angled pipewort, beaked spike-rush, and carnivorous sundew and bladderwort, the tiny *Nanothemis bella* dragonfly, and the eastern mud turtle.²⁵

The Lower Tidewater Region, including the cities of Norfolk and Virginia Beach, has extensive urban development surrounded by agricultural and conservation lands. Nearly 20 percent of undeveloped dry land at this site is at risk of inundation, mostly as rivers widen and transitional marsh and saltmarsh expand. While these undeveloped lands provide opportunities for habitats to migrate inland, pressure to develop some of these lands will likely increase because human population in this part of Virginia is projected to grow considerably in the coming decades.²⁶ Proactive measures to identify and protect lands where habitats can migrate will be critically

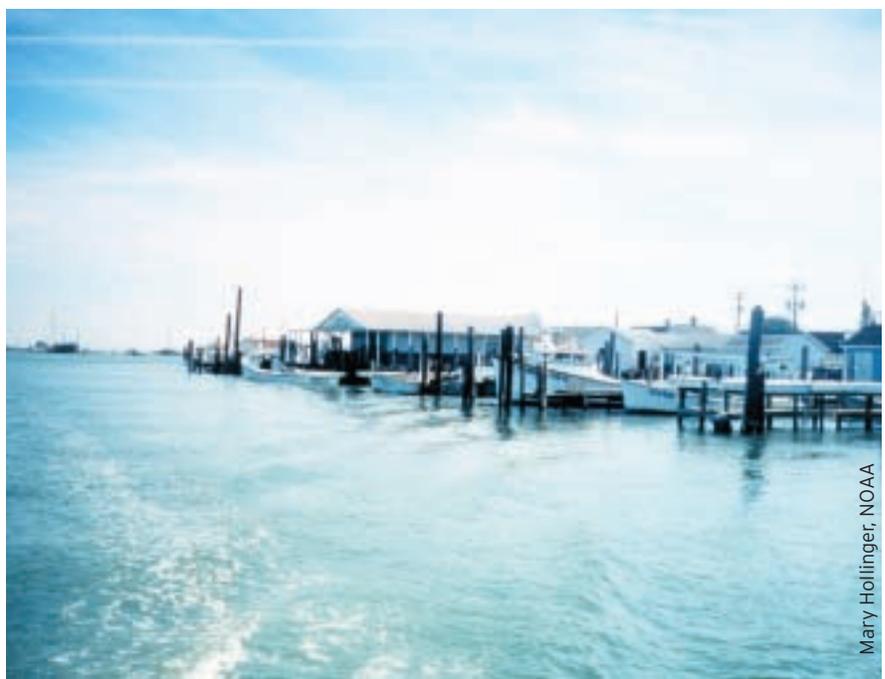


The Lower Tidewater Region: Initial Condition



The Lower Tidewater Region: Year 2100 (27.2 inches)

important. In addition, the region is projected to face a 79 percent loss of ocean beach by 2100, without extensive beach re-nourishment.²⁷



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PROJECTED CHANGES IN COASTAL HABITAT BY 2100 WITH A 27.2-INCH SEA-LEVEL RISE

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		DRY LAND	FRESHWATER HABITATS				SALTWATER HABITATS				OPEN WATER
		Undeveloped dry land	Tidal fresh marsh	Tidal swamp	Brackish marsh	Tidal flats	Estuarine beach	Ocean beach	Transitional saltmarsh	Saltmarsh	Estuarine open water
Delaware Bay	Acres change	-40,800	-236	-5,000	-112,000	+27,400	+2,540	+44	+5,990	+46,100	+59,100
	Relative change	-7%	-6%	-32%	-92%	+15-fold	+232%	+19%	+5-fold	+3-fold	+14%
Maryland Shore	Acres change	-16,400	-31	-4,240	-16,000	-1,100	-7,800	-180	+2,100	+5,030	+35,500
	Relative change	-6%	-18%	-57%	-61%	-51%	-79%	-24%	+224%	+235%	+39%
Blackwater National Wildlife Refuge and Surrounding Region	Acres change	-32,000	-750	-6,420	-33,100	+2,190	+1,540	NA	+1,440	+14,500	+48,700
	Relative change	-39%	-92%	-94%	-94%	+12-fold	+22-fold	NA	+27%	+87-fold	+50%
Tangier Sound Region	Acres change	-9,390	-72	-3,220	-18,900	-1,900	+290	NA	+1,530	+4,810	+26,600
	Relative change	-17%	-59%	-85%	-83%	-96%	+53%	NA	+133%	+162%	+30%
Virginia's Eastern Shore	Acres change	-13,800	NA	-440	-19,300	-7,890	-23,800	-970	+2,810	-13,900	+69,300
	Relative change	-18%	NA	-20%	-95%	-47%	-93%	-82%	+158%	-87%	+54%
Upper Tidewater Region	Acres change	-18,460	-8	-680	-8,130	-1,940	+1,860	NA	+4,370	+2,260	+15,740
	Relative change	-17%	-3%	-30%	-85%	-76%	+8-fold	NA	+11-fold	+12-fold	+14%
Lower Tidewater Region (Norfolk and Virginia Beach)	Acres change	-10,780	-17	-2,290	-890	-740	+560	-87	+1,170	+4,040	+5,360
	Relative change	-19%	-38%	-83%	-29%	-67%	+4-fold	-79%	+14-fold	+255-fold	+10%

Impacts on Fish and Wildlife

Hundreds of species of fish, invertebrates, birds, and other animals are at risk from sea-level rise in the Chesapeake Bay.²⁸ Some species will be affected directly by lost habitat, while others will be affected indirectly by widespread shifts in ecosystem composition and the regional food web.²⁹ Although predicting how each species will react to the potential habitat changes is difficult, it is possible to identify those species that are particularly vulnerable given their relative dependence on the most threatened habitats.

Fish and shellfish will be impacted by the major shifts in coastal marshes and significant loss of beaches brought on by sea-level rise. Changes to coastal marshes could have far-reaching effects on the region's food web: decomposing vegetation in these marshes provides an important source of nutrition for numerous invertebrates and small fish, which go on to feed rockfish, menhaden, blue crab, and other species. An estimated 66 percent of the region's commercial fish also depend on coastal marshes for nursery and spawning grounds,

including Atlantic menhaden, bluefish, flounder, spot, mullet, croaker, and rockfish.³⁰ Beaches around the Chesapeake Bay—many of which are especially vulnerable to sea-level rise—are important spawning habitat for the American horseshoe crab (a species that has existed nearly unchanged in the region for at least 250 million years) and fish species such as killfish, mummichog, rockfish, perch, herring, and silversides.³¹ In addition, tidal flats support worms, clams, snails, and other species that are critical food sources for a plethora of fish and wildlife.



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Waterfowl that migrate in the Atlantic Flyway use the Chesapeake Bay as an important stopover and wintering destination, while mallards and American black ducks nest here.³² A decline in tidal freshwater marshes in the region due to sea-level rise could be particularly harmful to the American black duck, whose populations are already low due to habitat loss from agriculture and development.³³ Seagrass losses associated in part with sea-level rise will be particularly devastating for those species that depend on submerged aquatic vegetation for food, including redhead, northern pintail, American wigeon, American black duck, ruddy duck, and canvasback.

Other birds that reside in the Chesapeake Bay's coastal marshes



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and beaches could also be affected. Loss of coastal marsh habitat could limit food sources and increase vulnerability to predators (by reducing available cover) for wading birds, such as great blue herons and snowy egrets, as well as marsh-nesting species, including clapper rail, black rail, least bittern, Forster's tern, and laughing gull.³⁴ In addition, the projected loss of beaches and tidal flats throughout the Chesapeake Bay region poses a serious threat to migratory shorebirds that forage and nest in these habitats.³⁵ Species at risk include red knot, piping plover,

American oystercatcher, ruddy turnstone, sanderling, and sandpipers.³⁶

Sea turtles rely on beaches around the Chesapeake Bay for critical nesting habitat. Widespread loss of the region's beaches projected under even modest sea-level rise scenarios would shrink important habitat for endangered turtle species, such as the loggerhead and Kemp's ridley sea turtles. In addition, the considerable loss of brackish marshes projected for the region could have a devastating impact on the native northern diamondback terrapin, which relies exclusively on these habitats.

Mammals, including the muskrat, beaver, river otter, and dolphins, depend on the region's marshes and other aquatic habitats. In addition, the Delmarva Peninsula to the east of the bay is the exclusive habitat for the endangered Delmarva fox squirrel.³⁷ The projected changes in coastal habitats will likely affect these species both directly, through loss of habitat, and indirectly, through changes in the regional food web.



Tim McCabe, USFWS

A Plan of Action for the Chesapeake Bay: Managing our Coastline and Habitats in the Face of Global Warming

Sea-level rise needs to be a major consideration in the region's coastal management and ecological restoration plans. Maryland has taken an important first step by establishing a state-wide *Sea-level Rise Response Strategy*, which has laid out a number of recommended actions.³⁸ Virginia's newly formed Governor's Commission on Climate Change is considering sea-level rise impacts on the state's coastal areas and has the opportunity to develop a similar strategy. These strategies need to be accompanied by federal, state, and local policies (see page 10) to ensure that the recommended actions are achieved.

Local, state, and federal agencies will need to identify appropriate response strategies on a site-specific basis. By identifying which locations and habitats in the bay region are especially vulnerable, this summary and the accompanying technical report will be an important tool for informing the development of these strategies. In particular, NWF's modeling results can help resource managers identify locations around the Chesapeake Bay region where the following actions should be undertaken to protect coastal habitats:

- **Preserve the ability of habitats to migrate inland as sea levels rise.**

We need to identify and protect expanded "buffers" along coasts and rivers, capitalizing on locations with little or no development, such as marginal agricultural lands, and where land acquisition and rolling easements might make sense. To protect both people and habitats, state and local agencies must also develop specific measures to

discourage development in vulnerable areas, such as those identified in this study.

- **Facilitate natural sediment build-up and artificial replenishment of sediments in coastal wetlands and beaches.**

We may be able to preserve habitats in some areas by restoring natural replenishment of sediments, for example, by removing seawalls, reforesting riparian areas, or reconsidering the use of river dams. Other areas may benefit from beach re-nourishment and the use of dredged materials to replenish coastal marshes, but only if rigorous environmental standards are in place to ensure that the projects do not use contaminated sediments, introduce invasive species, erode too quickly, or cause other ecological harm.

- **Improve the resiliency of fish and wildlife species by maintaining a diverse array of habitats.**

This study underscores how the Chesapeake Bay's coastal habitats are interconnected and how their interdependencies will become more

critical as sea-level rise forces habitat migration. Ultimately, we need to manage our coasts as functioning ecosystems with multiple linkages among habitats and species, rather than focusing separately on individual habitat types and species. These model results identify several places—like Blackwater National Wildlife Refuge and Virginia's Eastern Shore—that could experience significant shifts to less-diverse habitats, and therefore should be priority candidates for ecological restoration and protection projects.

Fortunately, we have the opportunity to act now to ensure that the Chesapeake Bay's precious coastal habitats, and the ecological and economic benefits they provide, will endure for our children and grandchildren. By taking sea-level rise into consideration when making decisions about the future of the Chesapeake Bay's coastal communities and resources, we can avoid costly and irreversible consequences for bay residents and the area's natural wonders.



POLICY RECOMMENDATIONS TO HELP VIRGINIA AND MARYLAND PREPARE FOR SEA-LEVEL RISE

(from NWF's 2007 report *The Chesapeake Bay and Global Warming: A Paradise Lost for Hunters, Anglers, and Outdoor Enthusiasts?*)

FEDERAL ACTIONS:

- Congress should reauthorize the **Coastal Zone Management Act** to require relevant state agencies to consider sea-level rise in coastal management plans to qualify for federal funding; prohibit federal subsidization of infrastructure development and coastal armoring in ecologically sensitive areas; and encourage public and private land acquisition of coastal habitats and upland buffers.
- The **Federal Emergency Management Agency** should remap potential hazard areas in coastal zones to reflect anticipated sea-level rise, taking into account potential storm surge impacts, and establish policies to reduce or eliminate federal flood insurance for new construction and rebuilding in high-risk areas.
- Congress should expand the **Coastal Barrier Resources system** to discourage new development in areas needed to buffer natural resources and existing development from sea-level rise. Such areas should be denied federal subsidies such as federal flood insurance, disaster relief, and loans for sewer, water, and highway construction.



Natural Resources Conservation Service

STATE AND LOCAL ACTIONS:

- Maryland and Virginia should enact new legislation requiring local governments to consider sea-level rise when amending their plans for coastal land use, open space, wetland protection policies, and other relevant activities.
- The Virginia Marine Resources Commission and the Maryland Department of Natural Resources in conjunction with the Maryland Department of the Environment should develop state tidal wetlands conservation and restoration plans that promote designation of wetland migration corridors and remove and discourage use of hard shoreline erosion structures in coastal marsh environments.
- The Maryland Department of Natural Resources should expand Maryland's Critical Area buffer designation and the Virginia Department of Conservation and Recreation should expand Virginia's Resources Protection Area buffer designations beyond the current 100-foot requirement to accommodate impacts of sea-level rise. States should also expand enforcement of current regulations and prevent any attempts to weaken these provisions in relevant legislation.
- State and local agencies should establish policies such as rolling easements or mandatory setbacks to discourage new development in vulnerable coastal areas.



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Endnotes

- ¹The Scientific and Technical Advisory Committee (STAC). 2003. *Chesapeake Futures: Choices for the 21st Century* (Annapolis, MD: Chesapeake Bay Program).
- ²Virginia Department of Conservation and Recreation (DCR). 2007. *2007 Virginia Outdoors Plan* (Richmond, VA: Virginia DCR).
- ³Perry, M.C., and A.S. Deller. 1995. "Waterfowl Population Trends in the Chesapeake Bay Area." in P. Hill and S. Nelson, eds., *Toward a Sustainable Coastal Watershed: The Chesapeake Experiment. Proceedings of a Conference. Chesapeake Research Consortium Publication No. 149* (Edgewater, MD: Chesapeake Research Consortium): 490-500.
- ⁴Najjar, R.G., et al. 2000. "The Potential Impacts of Climate Change on the Mid-Atlantic Coastal Region." *Climate Research* 14: 219-233.
- ⁵STAC, 2003.
- ⁶Intergovernmental Panel on Climate Change (IPCC). 2007a. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [S.D. Solomon, et al., eds.] (Cambridge, UK: Cambridge University Press).
- ⁷Hayhoe, K., et al. 2007. "Past and Future Changes in Climate and Hydrological Indicators in the U.S. Northeast." *Climate Dynamics* 28: 381-407; and Groisman, P.Y., et al. 2004. "Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from In Situ Observations." *Journal of Hydrometeorology* 5: 64-84.
- ⁸Fisher, A., et al. 2000. *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change: Mid-Atlantic Foundations, Chapter 7: Coastal Zones* (University Park, PA: Pennsylvania State University Press).
- ⁹Zervas, C..E. 2001. *Sea Level Variations of the United States 1954-1999, NOAA Technical Report NOS CO-OPS 36* (Silver Spring, MD: National Oceanic and Atmospheric Administration).
- ¹⁰U.S. Environmental Protection Agency, National Park Service, and the U.S. Fish and Wildlife Service. "Climate Change, Wildlife, and Wildlands Case Study: Chesapeake Bay and Assateague Island." *Climate Change, Wildlife, and Wildlands: A Toolkit for Teachers and Interpreters* <http://www.epa.gov/climatechange/wywd/ORWKit.html> (accessed March 11, 2008).
- ¹¹Chen, J.L., C.R. Wilson, and B.D. Tapley. 2006. "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet." *Science* 313: 1958-60; Otto-Bliesner, B.L., et al. 2006. "Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation." *Science* 311: 1747-50; Overpeck, J.T., et al. 2006. "Paleoclimatic Evidence for Future Ice-sheet Instability and Rapid Sea-level Rise." *Science* 311: 1747-50; Rignot, E., and P. Kanagaratnam. 2006. "Changes in the Velocity Structure of the Greenland Ice Sheet." *Science* 311: 986-90.
- ¹²Cahoon, D.R. 2008. "Factors Affecting Coastal Wetland Loss and Restoration." Chapter 12 in *Synthesis of U.S. Geological Survey Science for the Chesapeake Bay Ecosystem and Implications for Environmental Management* (Washington, D.C.: U.S. Geological Survey).
- ¹³Callaway, J.C., et al. 2007. "Emerging Issues for the Restoration of Tidal Marsh Ecosystems in the Context of Predicted Climate Change." *Madroño* 54: 234-248.
- ¹⁴Kearney, M.S. 2006. "The Potential for Significant Impacts on Chesapeake Bay." *Scientific Symposium Presentation Abstracts, Washington Summit on Climate Stabilization, September 18-21, 2006* (Washington, D.C.: Climate Institute).
- ¹⁵Cahoon, D.R., et al. 1998. "Global Climate Change and Sea-Level Rise: Estimating the Potential for Submergence of Coastal Wetlands." Chapter 3 in *Vulnerability of Coastal Wetlands in the Southeastern United States* (Washington, D.C.: U.S. Geological Survey).
- ¹⁶Stevenson, J.C., and M.S. Kearney. 2008. "Impacts of Global Climate Change and Sea-Level Rise on Tidal Wetlands." Pending chapter of manuscript by University of California Press.
- ¹⁷Najjar, et al. 2000.
- ¹⁸Titus, J.G. 1998. "Rising Seas, Coastal Erosion, and the Takings Clause: How to Save Wetlands without Hurting Property Owners." *Maryland Law Review* 57: 1281-1399.
- ¹⁹*Scientific Review of the Prescribed Fire Program at Blackwater National Wildlife Refuge* (Chesapeake Marshlands NWR Complex) and Fishing Bay Wildlife Management Area, February 22, 2005, <http://www.fws.gov/blackwater/pdf/scientificreviewfire> (accessed February 11, 2008).
- ²⁰Kearney, Grace, and Stevenson, 1988.
- ²¹Strange, et al., 2008.
- ²²Ibid.
- ²³Stevenson, Kearney, and Koch, 2002; and Short, F.T., and S. Wyllie-Echeverria. 2000. "Global Seagrass Declines and Effects of Climate Change." in C.R.C. Sheppard, ed., *Seas at the Millennium: An Environmental Evaluation, Vol III* (Amsterdam: Pergamon, Elsevier): 10-11.
- ²⁴Virginia DCR. "Virginia's Rare Natural Environments." *Natural Heritage Resources Fact Sheet*, http://www.dcr.virginia.gov/natural_heritage/documents/fsslfen.pdf (accessed March 14, 2008).
- ²⁵Ibid.
- ²⁶Virginia DCR, 2007.
- ²⁷Hardaway, C.S., et al. 2005. *Shoreline Evolution, Chesapeake Bay Shoreline, City of Virginia Beach, Virginia* (Gloucester Point, VA: Virginia Institute of Marine Sciences, College of William and Mary).
- ²⁸Strange, E.M., et al. 2008. *Mid-Atlantic Coastal Habitats and Environmental Implications of Sea Level Rise. Section 3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1.* J.G. Titus and E.M. Strange (eds.) EPA 430R07004. (Washington, D.C.: U.S. EPA).
- ²⁹Rogers, C.E. and J.P. McCarty. 2000. "Climate Change and Ecosystems of the Mid-Atlantic Region." *Climate Research* 14: 235-244.
- ³⁰WRC 4. "About Watersheds - Wetlands." *Watersheds: Where the Atmosphere Meets the Earth.* http://wrc.iewatershed.com/index.php?pagename=education_about_14b (accessed March 10, 2008).
- ³¹Strange, et al., 2008.
- ³²Perry, M.C. 2008. "Changes in Food and Habitats of Waterbirds." Chapter 14 in *Synthesis of U.S. Geological Survey Science for the Chesapeake Bay Ecosystem and Implications for Environmental Management* (Washington, D.C.: U.S. Geological Survey).
- ³³Erwin, R.M., et al. 2006. "High Tides and Rising Seas: Potential Effects on Estuarine Waterbirds." In R. Greenberg, et al., eds. *Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation. Studies in Avian Biology No. 32* (Riverside, CA: Cooper Ornithological Society).
- ³⁴Strange, et al., 2008 ; Erwin, et al., 2006.
- ³⁵Galbraith, H., et al. 2005. "Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds." *USDA Forest Service General Technical Report. PSW-GTR-191: 1119-1122.*
- ³⁶Strange, et al., 2008.
- ³⁷Chesapeake Bay Program, "About the Bay: Mammals." <http://www.chesapeakebay.net/baybio.htm> (accessed March 14, 2008).
- ³⁸Johnson, Z.P. 2000. *A Sea Level Rise Response Strategy for the State of Maryland* (Annapolis, MD: Maryland Department of Natural Resources).



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