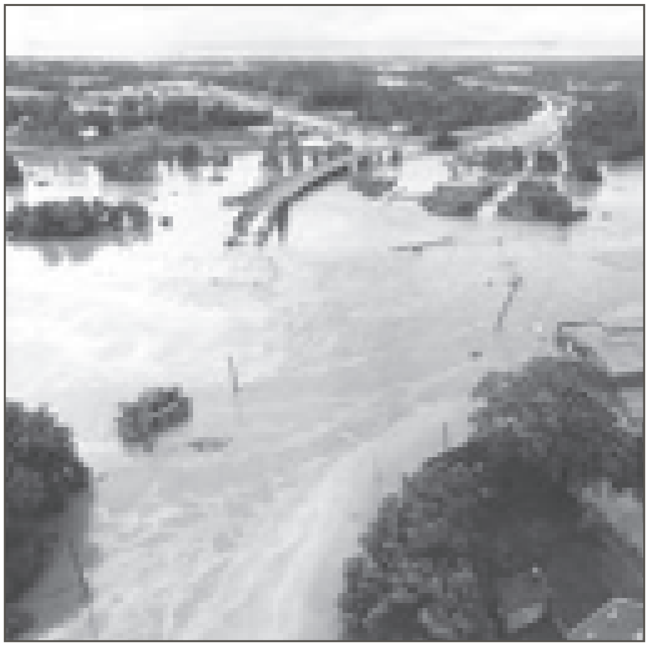
Chapter 3

Hazard Assessment

Monument Street Sinkhole, Baltimore City *Source: Baltimore Sun*



Destruction from Hurricane Agnes -Howard County *Source: Lloyd Pearson*

Hazard identification is the process which identifies and defines natural hazards that threaten the City of Baltimore. The hazard identification process looks at past hazard events—including an analysis of current hazards in addition to predicted threats due to climate change—and integrates damages and/or consequences that result from each hazard such as the destroyed homes, damaged trees, and compromised utility systems. Hazard identification includes the extent (severity) and probability (likelihood of occurrence) of each hazard, as well as the location of each hazard. Additionally, the process incorporates a brief explanation for hazards that are not particularly relevant for Baltimore's specific geography. For example, volcanic eruptions are not a hazard that the City of Baltimore faces now or in the near future.

In order to determine the most feasible and effective mitigation and adaptation recommendations for Baltimore, natural hazards which threaten the City had to be identified and defined, and their historical impacts analyzed. This chapter provides the following:

- Identification of hazards likely to affect the City of Baltimore;
- Profiles of the extent and severity of hazard events that have occurred in the City;
- Maps of specific locations where hazards occur; and
- Identification of predicted changes due to a changing climate.

Identification and Profile of Current Natural Hazards in Baltimore City

The process of identifying hazards included a variety of considerations and sources. The Federal Emergency Management Agency (FEMA) and the Maryland Emergency Management Agency (MEMA) provided Baltimore City with a preliminary list of natural hazards for this assessment. Based on historical data, as well as information provided by the National Oceanic and Atmospheric Administration (NOAA) and the State regarding anticipated climate impacts, city planners developed a draft list of hazards for consideration. Members of the Advisory Committee also provided input with regard to analysis of NOAA climate and weather data as recorded in the past 100 years. This was used as a baseline for comparison to changes in local climate projected to occur over the next 25 to 50 years. The analysis also incorporated most probable temperature and precipitation scenarios for the City through the year 2100 as synthesized from the most recent projections contained in the 2012 Intergovernmental Panel on Climate Change (IPCC) Report.

Further consideration was given to the apparent increase in frequency of high-impact, "no-notice" weather events to affect Baltimore and the State of Maryland since 1990. Relative to time periods prior to 1990, Baltimore has experienced a rise in frequency of high snow-accumulation winter storms, increasing frequency of severe weather outbreaks, as well as a rising number of higher average temperature readings on days that record highs are observed. The following table lists each hazard addressed in the preliminary investigation and identifies which hazards will be covered in this plan.

"NO-NOTICE" INCIDENTS

A "no-notice" incident is one that occurs unexpectedly or with minimal warning. Incidents with typically predictable patterns can also become no-notice incidents when their behaviors or patterns differ from what had been predicted or expected. Due to the nature of no-notice events, the ability of emergency responders to react in a timely manner may be challenged.

Table 3–9 Preliminary Investigation

Identified Hazard	Comments	Treatment in Plan
Avalanche	Lack of mountainous terrain makes hazard improbable in Baltimore City.	Not included in the plan
Air Quality	Baltimore has very poor air quality which significantly affects residents	Addressed in "Extreme Heat" hazard profile
Coastal Erosion	Many of the city's shorelines have been bulkheaded or do not have the wave action that lead to erosion.	Not included in the plan
Coastal Storm	Past experience has shown the hazard is a threat to Baltimore City.	Addressed in "Coastal Hazards" hazard profile
Dam Failure	Baltimore City owns and operates several dams.	Addressed in "Flooding" hazard profile
Drought	Baltimore City has had experiences with drought.	Addressed in "Precipitation Variability" hazard profile
Earthquake	Interview with Maryland Geological Survey indicated that hazard may affect Baltimore City.	Addressed in "Land" hazard profile
Expansive Soils	Interview with Maryland Geological Survey indicated that hazard does not significantly affect Baltimore City.	Not included in the plan
Extreme Heat	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Extreme Heat" hazard profile
Flood	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Flooding" hazard profile
Hailstorm	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Precipitation Variability" hazard profile
Hurricane	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Coastal Hazards" hazard profile
Land Subsidence	Interview with Maryland Geological Survey indicated that hazard does not significantly affect Baltimore City.	Not included in the plan
Landslide/Land Slump	Interview with Maryland Geological Survey indicates that land slump may affect Baltimore City.	Addressed in "Land" hazard profile
Severe Winter Storm	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Precipitation Variability" hazard profile
Tornado	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Wind" hazard profile
Tsunami	According to MEMA tsunamis are of concern along the East Coast of the United States.	Addressed in "Coastal Hazards" profile
Volcano	Interview with Maryland Geological Survey indicated that hazard does not significantly affect Baltimore City	Not included in the plan
Wildfire	While Baltimore has some forests, they are not huge, uninterrupted tracts of wildland. Baltimore does not have other elements that generate or spread wildfires, like arid climate, softwood/ conifer trees, large expanses of steep slopes (>40%), or prolonged drought.	Not included in the plan
Windstorm	Past experience has shown the hazard may significantly affect Baltimore City.	Addressed in "Wind" hazard profile

List of Hazards:

This Plan will address the following natural hazards by analysis of impacts on Baltimore City and recommendations for mitigation and adaptation strategies:

Flooding:	Flooding and Dam Failure
Coastal Hazards:	Tropical Storms and Hurricanes; Sea Level Rise; and Storm Surge/Coastal Inundation; Tsunami
Precipitation Variability:	Precipitation; Thunderstorms, with Lightning and Hail; Winter Storms and Nor'Easters; Drought
Wind:	Associated with Storms; Derechos; Tornados
Extreme Heat:	Heat and Air Quality
Land:	Earthquakes; Landslides; Karst/Sinkholes

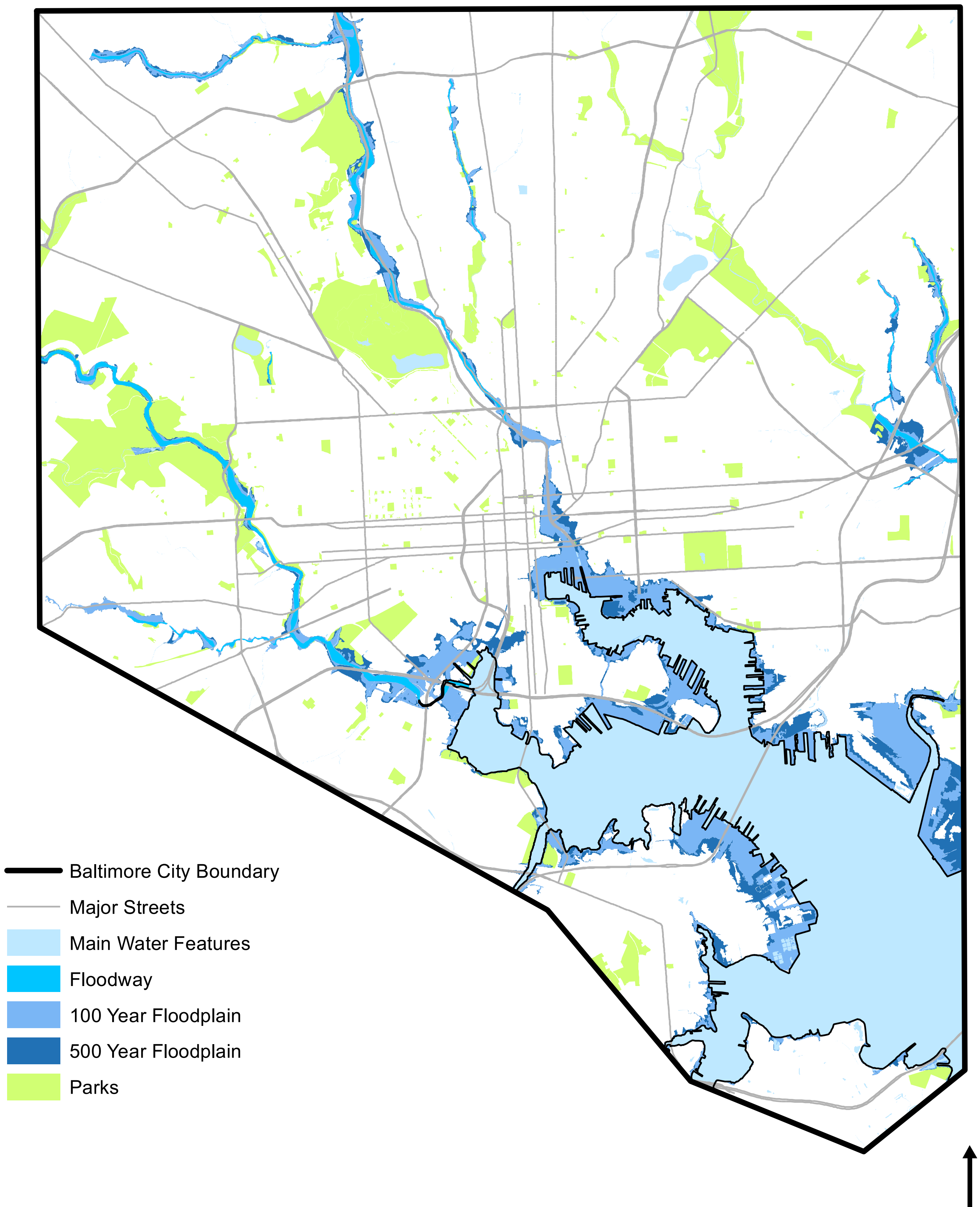
Image of flooding and subsequent damage in Colorado *Source: The Associated Press*

Image of the Jones Falls flooding in Mount Washington, Baltimore *Source: Flickr.com*

Flooding

Flooding occurs when rivers, creeks, streams, ditches, or other hydrological features receive too much water. Three categories of flood are common in the State of Maryland: flash, riverine, and coastal. In Baltimore, major flooding events are the result of riverine flooding along the stream tributaries of the Patapsco River — including the Gwynns Falls and the Jones Falls, as well as their own tributaries — or from tidal flooding in the Northwest Harbor and Middle Branch of the Patapsco River.[1] Riverine flooding, usually from persistent rain or snowmelt, forces excess water beyond the water body and into the adjacent floodplain.[2] According to the 2012 FEMA Report, *Flood Insurance Study* (FIS) for the City of Baltimore, riverine flooding in the City is most often attributed to the following factors: "urbanization, which creates more runoff from impervious zones and higher, sharper flood peaks; stream channel encroachments, which include structures within the floodplain and undersized railroad and roadway bridges; and inadequate storm sewer drainage." Along the City's waterfront, high tides amplify flooding events.[3] Figure 3–1 delineates the Baltimore City Floodway along with the FEMA-designated 100- and 500-year floodplain areas. 100-year floods are those which have a 1.0 percent chance of being equaled or exceeded in scale in any given year; whereas the 500-year flood designation relates to a flood with an approximate 0.2 percent chance of being equaled or exceeded.[4]

Most of Baltimore's recorded floods have been the result of either flash flooding during sudden, short-lived rainstorms, or localized flooding due to poor drainage and stormwater management. *The Flood Insurance Study for the City of Baltimore* indicates that major historic flood events occurred in 1817, 1837, 1863, 1868, 1933, 1955, 1972, and 1975. These floods led to the loss of human life and caused significant damage to dwellings, industries, and infrastructure. In August 1817, flooding along the Jones Falls swept away homes, bridges, and livestock. Floodwaters during this event were reportedly between 12 and 20 feet above normal levels.[5] Similarly, the Jones Falls rose 20 feet during the flood of July 1868, when the river claimed more than 50 lives and caused millions of dollars in damages, primarily in downtown Baltimore. In July 1923, recorded flood damage was even more immense; and the flood of 1966 took 39 lives.[6] A list of additional major flood events, dating back to 1952, is found in Table 3–10 Historic Floods in Baltimore City with Damage Information on the following pages.



Created: June 25, 2013
Source: Baltimore City Enterprise Geographic Information Services

Figure 3–1 Baltimore City Floodway

Table 3–10 Historic Floods in Baltimore City with Damage Information

Dates	Type	Location	Description	Cost
9/1/1952	Coastal, Flash, River	Regional	Hurricane Able cause major flooding and washed out the B&O Railroad in Baltimore. 11 barges were torn loose from their moorings in the harbor, and 21 vehicles were swept into the harbor.	$500,000
10/15/1954	Coastal, Flash, River	Regional	Hurricane Hazel killed 6 people in Maryland and dropped 5-6 inches of rain in 8 hours. Heavy winds caused 6 foot storm surge.	$28,000,000 in Maryland
8/13/1955	Coastal, Flash, River	Regional	Hurricane Connie caused wide-spread flooding throughout Maryland with 10 inches of rain in 72 hours and killed 16 people.	$33,900,000 in Baltimore City
8/1/1971 to 8/2/1971	Flash	Baltimore City and Baltimore County	Between 5 and 12.5 inches of rain over 8 hours. 16 deaths attributed to flooding. Storm closed major highways in the region, left 20,000 residents without power, and displaced hundreds.	Est. $1,000,000
6/23/1972	Coastal, Flash, River	Regional	Tropical Storm Agnes killed 21 throughout Maryland and dropped 8 inches of rain in one day.	$110,000,000 in Maryland, $3.5 Billion nationwide
9/22/1975 to 9/26/1975	Flash	Regional	The remnants of Hurricane Eloise stalled and combined with other storm systems, dropping 14 inches of rain in Westminster, MD between Sept. 22 and 26. 17 deaths attributed to flooding	Est. $300,000,000 throughout Mid-Atlantic
9/6/1979	Flash	Regional	Tropical Storm David spawned 8 tornadoes and multiple flash floods in the Baltimore area and killed 15 nationwide.	$320,000,000 nationwide
9/19/2003	Coastal, Flash	Regional	Hurricane Isabel caused extensive flash floods as well as a storm surge of 8 feet in Baltimore City. 15 businesses and 570 homes sustained major damage, and 100 structures collapsed. 8 deaths are attributed to the storm throughout Maryland.	$4,900,000 in Baltimore City, $945,000,000 nationwide
7/7/2004	Flash	Mt. Washington along the Jones Fall	21 vehicles lost in water, 54 911 calls for flooded basements	Unknown
6/25/2006 to 6/28/2006	Flash	Mt. Washington and Clipper Mill Rd.	The Jones Fall rose 9.8 feet in 4 hours and 15 minutes. 94 residents displaced.	Unknown

11/16/2006	Flash, Coastal	Regional	Mudslide on 295 NB near Waterview exit. I-83 NB from Fayette to Chase St. closed due to flooding. Harbor Hospital sustained minor flood damage.	Unknown
7/23/2008	Flash, Coastal	Patapsco Ave.	Heavy rain and high winds left 27,000 customers in the region without power. In Baltimore City, Part of the Vietnam Veterans Memorial Bridge was flooded, and traffic was redirected. I-83 closed at President and Monument Street due to standing water. Sinai Hospital emergency department sustained minor damage from flood waters.	Unknown
9/26/2008	Flash	Mt. Washington, Union Ave., and Clipper Mill Rd.	Major storm system with 45 mph gusts and 2 inches of rain. 100 Residents displaced, 15 businesses sustained damage.	Unknown
8/12/2010	Flash, Coastal	Regional	Heavy thunderstorms hit the region during morning rush hour and left 9500 customers without power. Several roadways closed due to flooding, including: Eastern Ave. and Highland Ave., Fleet St. between Caroline and Bond, Pulaski Highway at Monument St. and Moravia, and the 200 block of N. Lakewood Ave.	Unknown
3/10/2011	Flash	Mt. Washington, Union Ave., and Clipper Mill Rd.	2.5 inches of rain during evening rush hour forced evacuations and closed I-83 near Penn Station. Runoff from storm water infiltrated sanitary sewer causing 10,000 gallons of untreated sewage to spill. Dozens of basements flooded.	Unknown
4/16/2011	Coastal	Regional	Large series of storms spawning 100 tornados from North Carolina through the Mid-Atlantic caused flooding in Fells Point and the Inner Harbor and left 17,000 customers without power in Baltimore City.	Unknown
10/29/2012	Coastal	Regional	Hurricane Sandy caused flooding along Fells Point and the Inner Harbor with a moderate storm surge and 5.5 inches of rain.	$65 billion nationwide

The Jones Falls, especially where it passes through the Mt. Washington neighborhood of Baltimore, has been a recurrent flood threat to the adjacent structures. The historic mills that were sited at the edge of the river have since been converted into mixed use buildings which are now home to residents and successful businesses. These properties continue to be flooded; in recent years, severe flooding in Mt. Washington has occurred most notably in 2004, 2006, and 2008. Properties which frequently suffer damage from floods are referred to as "repetitive loss properties." FEMA identifies repetitive loss properties as those which have experienced two or more flood insurance claims of at least $1,000 within a 10-year period since 1978. There are 52 such properties in Baltimore City, and currently only 17 of those properties are insured by FEMA. Close to $10 million dollars in flood insurance claims have been attributed to these properties. Due to privacy concerns associated with flood insurance, the type of information that can be shared regarding repetitive loss properties is restricted. This information is considered to be legally privileged and confidential, and use is protected under the Privacy Act of 1974, 5 U.S.C. Section 552(a). However, while detailed property information may not be discussed, the location information may still be represented. Figure 3–2 Repetitive Loss Properties, notes the locations of Baltimore's repetitive loss properties. Note how these properties are clustered around the floodways and floodplains.

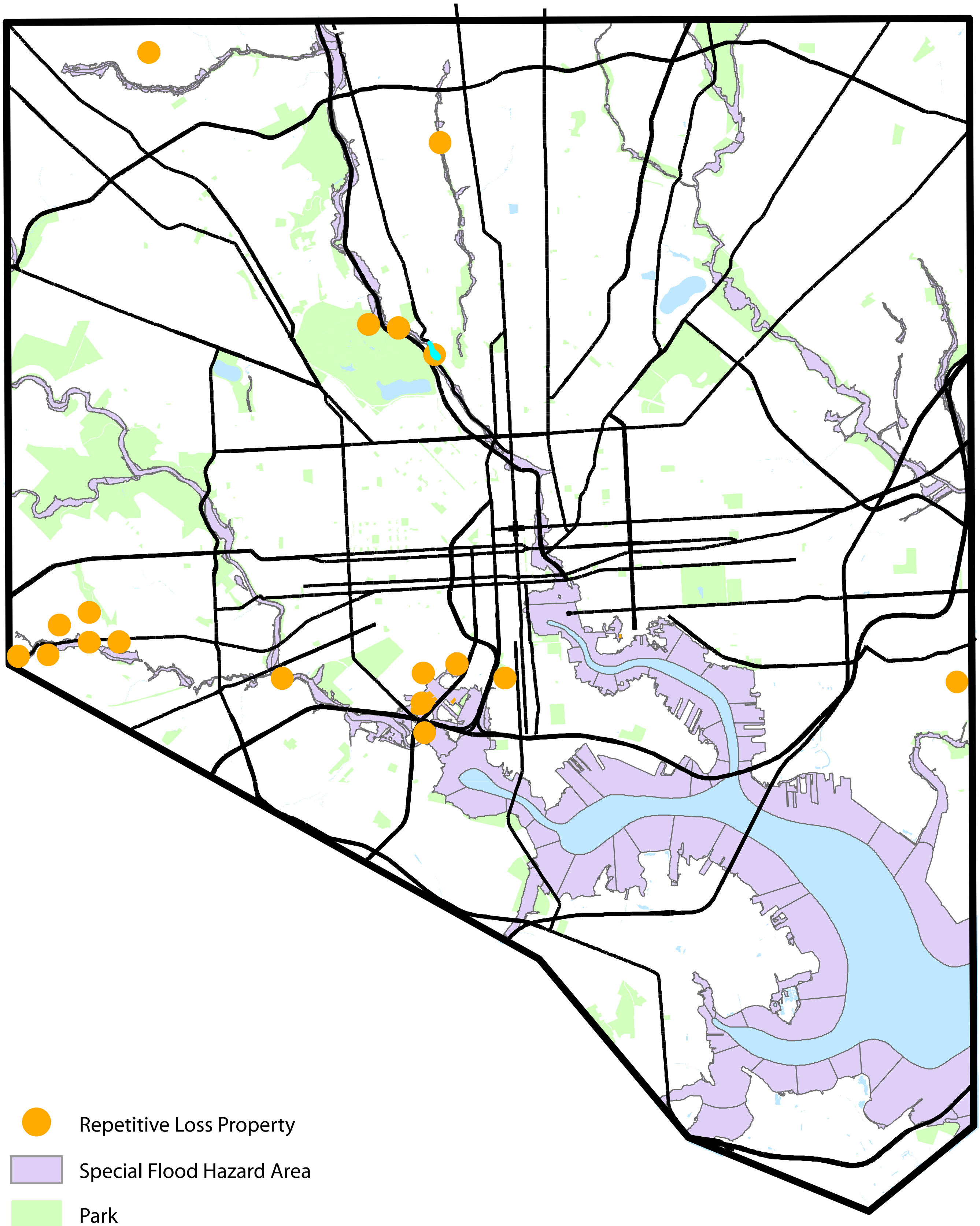


Figure 3–2 Repetitive Loss Properties

In Baltimore, tidal flooding usually occurs as a result of storm events, such as nor'easters or hurricanes (see Precipitation Variability Hazard Profile; see Coastal Hazards Profile). As an additional concern, flood maps indicate that some areas of tidal flooding are also affected by high velocity flooding. High velocity flooding, where floodwaters can move faster than five feet per second, can exacerbate flood damage. During the storm of 1933, downtown Baltimore was inundated by tides which arose 8.33 feet at Fort McHenry. Flooding during Tropical Storm Agnes, in June 1972, stands as one of Maryland's biggest natural disasters. In some areas, flood peaks were twice as high as the 100-year recurrence interval.[7] Statewide, Agnes caused $43 million in damages to public infrastructure and $66 million in damage to private property. Baltimore City alone suffered $33.9 million in losses.[8] More recently, in fall 2003, Hurricane Isabel hit Baltimore. At the time, the storm was referred to as the "perfect" 100-year tidal flood—meaning that floodwaters reached depths predicted for 100-year floods. The City's Flood Insurance Rate Maps reflected that the extent of Isabel's flooding corresponded to the adopted 100-year flood zone. The City was regulating development based on these maps. Fortunately, thanks to Baltimore City's freeboard requirements, buildings with first floors at or above the 1' freeboard elevation did not sustain major flooding damage, and only 16 flood insurance claims were filed. It is worth noting, that even through those maps reflect Isabel's impact as a 100-year storm, the new tidal floodplain analysis show that Isabel was a 500-year event.

Floods in Baltimore have forced evacuation, displaced hundreds of residents, overwhelmed emergency communication lines, and negatively impacted businesses. Major storm events and floods become even more menacing when critical emergency facilities are impacted, as was the case in November of 2006 and July of 2008 when different hospitals were impacted by floodwaters; or in 2012, when Sandy flooded research facilities at Johns Hopkins (though it had little impact on patient care facilities). This vulnerability must be taken into account as the City looks to the future. In Baltimore, 5.19 square miles of property (6.4 percent of the City's total land area) currently rests within the flood zone, while 3 percent of Baltimore's overall land — primarily in the Inner Harbor and the Fells Point Historic District — is within the coastal floodplain. By the end of the century, approximately 180 square miles of dry land along Maryland's coastline is expected to be inundated. Coupled with more frequent and extreme precipitation events (See Precipitation Variability Hazard Profile) these conditions could present a regular hazard.

Figure 3–3 The Jones Falls, Showing buildings that sit within the floodplain in orange

Dam Failure

As an aspect of flooding, risks associated with dam failure are considered in this plan. Dams are constructed to manage water storage, control flooding, and divert runoff into reservoirs upstream. Dams are sources of concentrated vulnerability and can lead to serious regional disasters when they fail. Dam failure is the collapse or breach of the dam structure, for which there is often either very little or no advance warning. While most dams in the Baltimore region have relatively small water volumes and failures would therefore have little or no repercussions, dams with larger storage volumes can have disastrous consequences should they fail.

Dam failures can be caused by any one or a combination of the following:

- Prolonged periods of rainfall and flooding (cause of most dam failures in the U.S.)
- Inadequate spillway capacity, resulting in excess overtopping flows.
- Internal erosion caused by embankment or foundation leakage or piping.
- Improper maintenance, including failure to remove trees, repair internal seepage problems, replace lost material from the cross section of the dam and abutments, or maintain gates, valves, and other operational components.
- Improper design, including the use of improper construction materials and construction practices.
- Negligent operation, including the failure to remove or open gates or valves during high flow periods.
- Failure of upstream dams in the same drainage basin.
- Landslides into reservoirs, which cause surges that result in overtopping.
- High winds, which can cause significant wave action and result in substantial erosion.
- Earthquakes, which typically cause longitudinal cracks at the tops of the embankments, thereby leading to structural failure (see the Land Hazards Profile).

Prettyboy Dam *Source: m3liss.wordpress.com*

Table 3–11 Baltimore City Dams by Waterway and Hazard Potential			
Dam Name	Waterway	Hazard Potential Classification	EAP
Druid Hill Lake	Offstream-Jones Falls	H	X
Guilford Reservoir	Offstream-Stony Run	H	X
Hillen Road Water Supply Lake	Offstream-Herring Run	H	X
Lake Ashburton	Gwynns Run	H	X
Lake Montebello	Offstream-Herring Run	S	
Lake Roland Dam	Jones Falls	H	X
Liberty Dam	North Branch, Patapsco River	H	X
Loch Raven Dam	Gunpowder River	H	X
Montebello Waste Water Lake	Offstream-TR-Herring Run	L	
Old Loch Raven Dam	Gunpowder River	L	
Pecks Branch Dam (Ashburton)	Offstream-Gwynns Run	H	X
Prettyboy Dam	Gunpowder Falls	H	X
Pikesville Reservoir	Offstream – Gwynns Falls	H	X
Mays Chapel Reservoir	Offstream – Jones Falls	H	X
Towson Reservoir	Offstream – Jones Falls	H	X
National Inventory of Dams, http://crunch.tec.army.mil/nid/webpages/nid.cfm and Hal Van Aller, P.E. of MDE Dam Safety Division			

In Maryland, most dams consist of an earthen embankment to retain water and a combination of spillways designed to convey water safely around or through the facility. The Baltimore City Department of Public Works owns and maintains the seven Public Works dams around the City. All of the City's dams are earthen (one is earthen with rockfill), and all but one are considered off-stream dams. The National Inventory of Dams, a database maintained by the U.S. Army Corps of Engineers, classifies one of the seven dams as being a low hazard, one as being a significant hazard, and five as high hazard dams. Low hazard potential dams are those where failure or improper operation would result in no probable loss of human life and low economic or environmental losses. Significant hazard potential dams are those where failure or improper operation would result in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns. High hazard potential dams are those where failure or improper operation will likely cause loss of human life. Table 3–11 Baltimore City Dams by Waterway and Hazard Potential details the names, associated waterways, and the hazard potential classification for all of the dams found within, or used and maintained by, Baltimore City. All Baltimore City dams classified as being high hazard potential have corresponding Emergency Action Plans (EAP).

Stanford University maintains the National Performance of Dams Program database which documents dam incidents. Incidents are defined as events that affect the structural and functional integrity of dams but which do not necessarily cause failure, and does not include ordinary maintenance and repair, vandalism, acts of war, recreational accidents, or sabotage. This database has no record of dam incidents for facilities in the City of Baltimore.

Figure 3–4 Tropical Storms and Hurricanes within 200 Nautical Miles of Baltimore City *Source: NOAA*

Coastal Hazards

Tropical Storms and Hurricanes

Tropical storms and hurricanes are very intense, low-pressure wind systems that form over tropical or sub-tropical waters. Both tropical storms and hurricanes are considered tropical cyclones; the distinction, however, is based on wind speeds and, typically, on the amount of destruction produced (i.e. the "impact"). Tropical storms are given a name when the maximum sustained wind speeds within the storm's eyewall reach or exceed 39 mph. If a tropical storm continues to grow in strength, and peak wind speeds reach 74 mph, it is then declared a hurricane.

The Saffir-Simpson Hurricane Intensity Scale (shown in Table 3–12 Saffir-Simpson Scale), categorizes intensities of hurricanes based on wind speed and the expected storm surge. A storm surge, one of the most damaging impacts of a coastal storm event, is an abnormal local rise in sea level, caused by deepening low pressure in the core of the storm that creates an extreme difference in barometric pressure between the tropical system and the atmospheric environment outside the system. As a result, a dome of water rises under the eye of the storm, and is eventually pushed onto the coastline as the storm makes landfall. The height of a surge is measured as the deviation (in feet) above average sea level. In extreme circumstances, storm surge can, and has exceeded a height of 25 feet in other areas around the world. Storm surge is especially damaging due to the combination of a high volume of water covering a large geographic area that is moving toward or across land at high velocity. According to NOAA, 9 out of every 10 deaths associated with coastal storms are caused by storm surge—demonstrating why this water phenomenon is often the greatest threat to life and property from a tropical system. As the scale demonstrates, when a storm grows more intense, the resulting storm surge is more likely to reach greater heights and bring more significant damage. Storm surge may also accompany significant coastal storms that are known along the east coast as "Nor'easters." (For a discussion of hazards associated with Nor'easters, see the Winter Storms and Climate Influences section below).

Figure 3–4 Tropical Storms and Hurricanes within 200 Nautical Miles of Baltimore City illustrates the paths of previous hurricanes that have come near the City, signifying storm magnitude by color. As it demonstrates, storms crossing directly through Baltimore are typically tropical or sub-tropical storms.

Coastal storm systems can persist for extended periods of time, and across great distances. As hurricanes are sometimes hundreds of miles across, their effects can be felt in areas that may be quite distant from the storm's center. Hurricane Agnes in 1972, for example, did not pass directly over Baltimore, but is still considered to be one of the most damaging hurricanes in Baltimore's history. At impact, Agnes was a Category 1 hurricane. Baltimore experienced widespread flash flooding and considerable riverine flooding. The State of Maryland reported 21 storm-related deaths and total public sector cost in excess of $110 million. In 2003, the region was hit by the Category 2 Tropical Cyclone, Isabel. In Baltimore City, Isabel's cost to the public sector totaled $4,883,364. Fifteen commercial properties and more than 570 homes were declared uninhabitable due to Isabel's major flood damage; while approximately 100 structural collapses occurred throughout the county. As an additional hazard, Tropical Storms and Hurricanes are also capable of spawning tornados. For example, in 1979, Tropical Storm David spawned 8 tornados in Maryland. Similarly, Hurricane Irene produced tornados near the Eastern Shore of Maryland.

As hurricanes and tropical storms near land, they may generate torrential rains, high winds, storm surge inundation, coastal flooding, and inland flooding. Hurricanes can also produce difficult-to-predict tornadoes within embedded rain bands (for a description of tornado hazards, see the Wind Hazard Profile). Depending on where a tropical system makes first landfall, coastal storms can lead to dangerous storm surges and inundation of low-lying land. In Baltimore, hurricanes and tropical storms have produced wind damage, riverine flooding along tributaries, and inundation of shorelines and harbors by way of intense storm surges.

Due to a combination of geographic and climatic factors, major hurricanes of Categories 3 and above generally begin to weaken upon reaching the Mid-Atlantic. Prior to making landfall, a storm may have rapid wind speeds — and may be classified as one or more categories higher, with much faster winds — than what is recorded once the storm makes landfall. 1969's Camille, for example, dropped from 165 mph to wind speeds of just 25 mph when passing over Baltimore. As they make landfall, however, wind speeds are diminished (1969's Camille went from 165 mph wind speeds to just 25 mph) and the category of storm often becomes lower. This change is demonstrated in Table 3–14 Tropical Storms and Hurricanes within 200 Nautical Miles of Baltimore City, which reveals key information about significant tropical storms and hurricanes that have passed within 200 nautical miles of Baltimore City since 1950. In the past 61 years, 51 hurricanes and other tropical

Table 3–12 Saffir-Simpson Scale

Category	Wind Speed	Storm Surge	Expected Damage
1	74-95 mph	4-5 ft.	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days
2	96-110 mph	6-8 ft.	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	111-129 mph	9-12 ft.	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	131-156 mph	13-18 ft.	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months
5	>157 mph	>18 ft.	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Derived from NOAA National Hurricane Center: Saffir-Simpson Scale (http://www.nhc.noaa.gov/aboutsshws.php) and Understanding Your Risks, FEMA 386-2, 2-23

Table 3–14 Tropical Storms and Hurricanes within 200 Nautical Miles of Baltimore City

Storm	Year	Start Date	End Date	Wind Speed (KTS)	Max Wind Speed	Category
ABLE	1952	Aug. 18	Sep. 2	40	90	TS
BARBARA	1953	Aug. 11	Aug. 16	65	95	H1
CAROL	1954	Aug. 25	Sep. 1	85	85	H2
HAZEL	1954	Oct. 5	Oct. 18	110	115	H3
CONNIE	1955	Aug. 3	Aug. 15	45	125	TS
DIANE	1955	Aug. 7	Aug. 21	45	105	TS
CINDY	1959	Jul. 5	Jul. 12	40	65	TS
GRACIE	1959	Sep. 20	Oct. 2	60	85	TS
BRENDA	1960	Jul. 28	Jul. 31	45	50	TS
DONNA	1960	Aug. 29	Sep. 13	95	140	H2
UNNAMED	1961	Sep. 12	Sep. 15	35	35	TS
DORIA	1967	Sep. 8	Sep. 21	50	75	TS
CAMILLE	1969	Aug. 14	Aug. 22	25	165	TD
ALMA	1970	May. 17	May. 27	25	70	TD
DORIA	1971	Aug. 20	Aug. 29	50	55	TS
GINGER	1971	Sep. 6	Oct. 5	30	95	TD
AGNES	1972	Jun. 14	Jun. 23	45-60	85	TS
BELLE	1976	Aug. 6	Aug. 10	90	105	H2
SUBTROP:SUBTROP 3 1976	1976	Sep. 13	Sep. 16	20	40	TD
BOB	1979	Jul. 9	Jul. 16	20	65	TD
DAVID	1979	Aug. 25	Sep. 7	40	150	TS
FREDERIC	1979	Aug. 29	Sep. 14	35	65	TS
BRET	1981	Jun. 29	Jul. 1	40	60	TS
DEAN	1983	Sep. 26	Sep. 30	55	55	TS
BOB	1985	Jul. 21	Jul. 25	30	65	TD
DANNY	1985	Aug. 12	Aug. 20	25	80	TD
GLORIA	1985	Sep. 16	Oct. 1	75	125	H1
HENRI	1985	Sep. 21	Sep. 24	35	50	TS
CHARLEY	1986	Aug. 13	Aug. 29	65	70	H1
CHRIS	1988	Aug. 21	Aug. 30	20	45	TD
DANIELLE	1992	Sep. 22	Sep. 26	40	55	TS
BERYL	1994	Aug. 14	Aug. 18	15	50	TD
BERTHA	1996	Jul. 5	Jul. 17	60	100	TS
FRAN	1996	Aug. 23	Sep. 9	40	105	TS
DENNIS	1999	Aug. 24	Sep. 8	20	90	TD
FLOYD	1999	Sep. 7	Sep. 19	60	135	TS
GORDON	2000	Sep. 14	Sep. 21	25	70	TD
HELENE	2000	Sep. 15	Sep. 25	40	60	TS
ALLISON	2001	Jun. 5	Jun. 18	30	50	TD
ISABEL	2003	Sep. 6	Sep. 19	65	140	H1
BONNIE	2004	Aug. 3	Aug. 13	30	30	TD
CHARLEY	2004	Aug. 9	Aug. 15	40	130	TS

GASTON	2004	Aug. 27	Sep. 2	35	65	TS
IVAN	2004	Sep. 2	Sep. 24	25	140	TD
JEANNE	2004	Sep. 13	Sep. 29	35	105	TS
CINDY	2005	Jul. 3	Jul. 11	30	65	TD
ERNESTO	2006	Aug. 24	Sep. 4	40	65	TS
BARRY	2007	May. 31	Jun. 5	40	50	TS
HANNA	2008	Aug. 28	Sep. 8	45	75	TS
IRENE	2011	Aug. 21	Aug. 29	65	105	H1
SANDY	2012	Oct. 21	Oct. 30	80	95	H1

storms have passed within 200 nautical miles of Baltimore, an annual frequency of 0.8 hurricane events. This chart indicates the Categories and wind speeds of systems as they approached and impacted Baltimore, as opposed to what may have been recorded prior to a system making landfall. To demonstrate the severe change in speed over land, maximum wind speeds have also been noted.

Since 1950, Baltimore has not suffered a direct hit by any storm greater than a Category 1 hurricane (though higher intensity storms had still passed within 200 nautical miles of the City). However, as noted, storms like Agnes and Isabel have caused great amounts of flooding and damage. Due to the unpredictable nature of storms, Category designation does not always accurately reflect a storm's potential damage in Baltimore. Indeed, severe damage has occurred to property and natural coastlines from less-than-major Category hurricanes. This damage is caused by a remnant storm surge decreasing more slowly than expected following the weakening of the land-falling storm.

It is important to note, however, that a storm's weakening allows "accumulated cyclone energy" (ACE) to quickly affect a much larger area as the storm nears land at higher latitudes. Thus, the weakening storm will undergo an expansion of the wind field and, while maximum sustained winds in the storm's core usually decrease, the overall area that is significantly affected by tropical storm force or hurricane force winds becomes much larger.

Hurricane Sandy, in October 2012, is one example of this phenomenon: in the day prior to landfall, the wind field expanded to a diameter greater than 1,000 miles. On October 28-29, portions of the City of Baltimore observed maximum wind gusts of 63 mph, with brief periods of sustained winds near tropical storm force of 39 mph. These winds were accompanied by extremely heavy downpours of rain. At the time, the center of Hurricane Sandy was east of Baltimore in the western Atlantic Ocean. This is one example of how an expanding wind field, even from a weakening tropical system, can generate multiple hazards hundreds of miles from the storm's center.

Additionally, Hurricane Sandy produced a spike of more than 3 feet in tidal rise at the Inner Harbor within a short period of time as the storm was passing to the north and east of Baltimore. Were a storm like Sandy to occur in 2025, 2050 or 2100, it would more easily inundate low laying areas with a similar, or even smaller, surge. Taking into consideration recent projections for sea level rise in Maryland, which suggests relative sea level rise could increase by as much as 5.7 feet by the end of the century, storm surge hazards will require significant mitigation strategies.[9] On top of this projected rise, even a low-end tropical storm could produce water damage greater than that from Isabel if construction measures are not incorporated immediately.

Baltimore's extensive hurricane history and the mapped hurricane inundation areas show that hurricanes are a significant hazard to the City. Additionally, hurricanes have the potential to have a considerable impact on human health. Table 3–15 Coastal Hazards - Injuries and Deaths, below, indicates that a total of 200 injuries and 1 fatality were caused by coastal hazards in recent decades.

Table 3–15 Coastal Hazards - Injuries and Deaths

County/City	Total Injuries	Total Deaths
Baltimore City	200	1

Source: Table 3-37, Maryland Emergency Management Agency, 2011: 127-128.

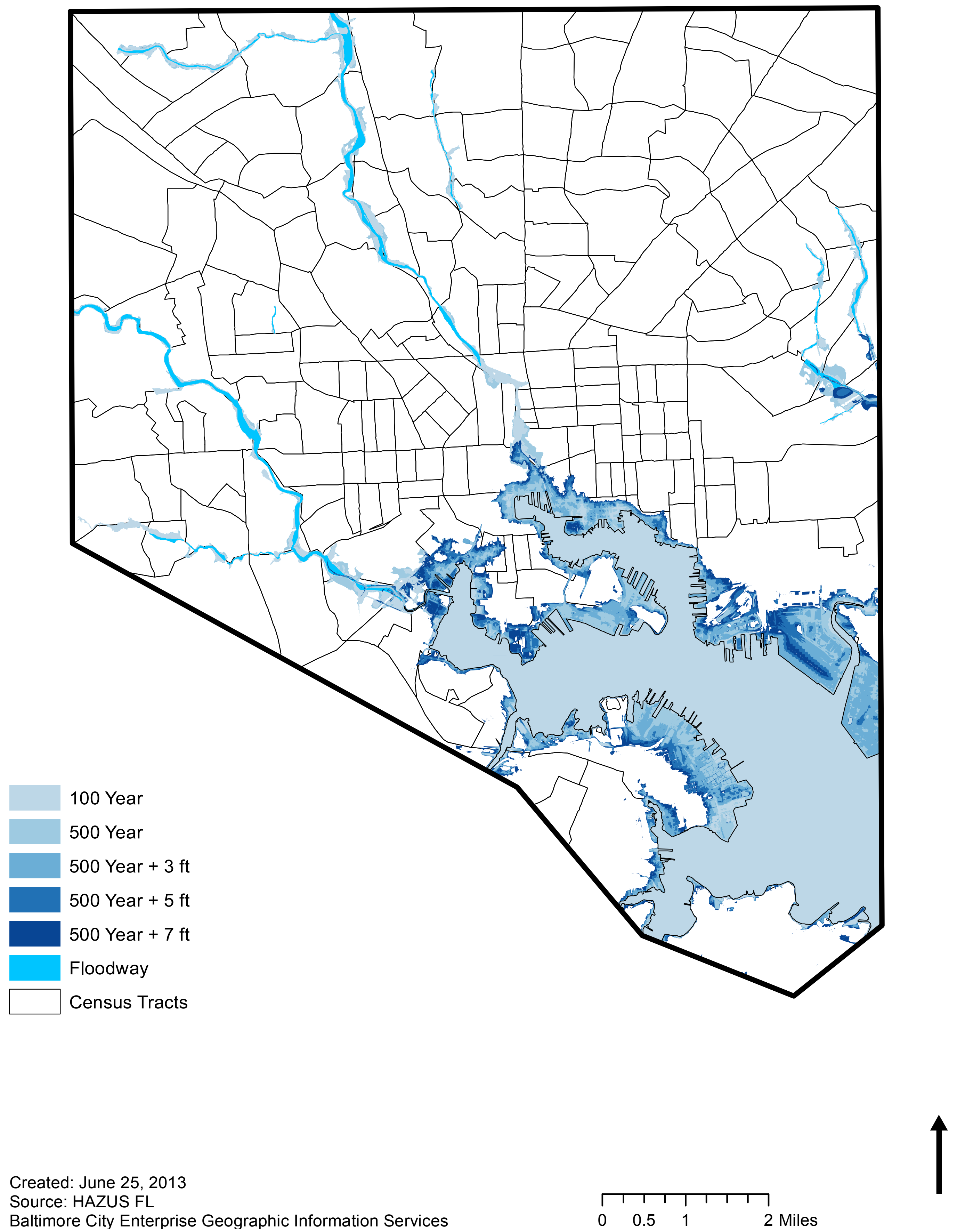
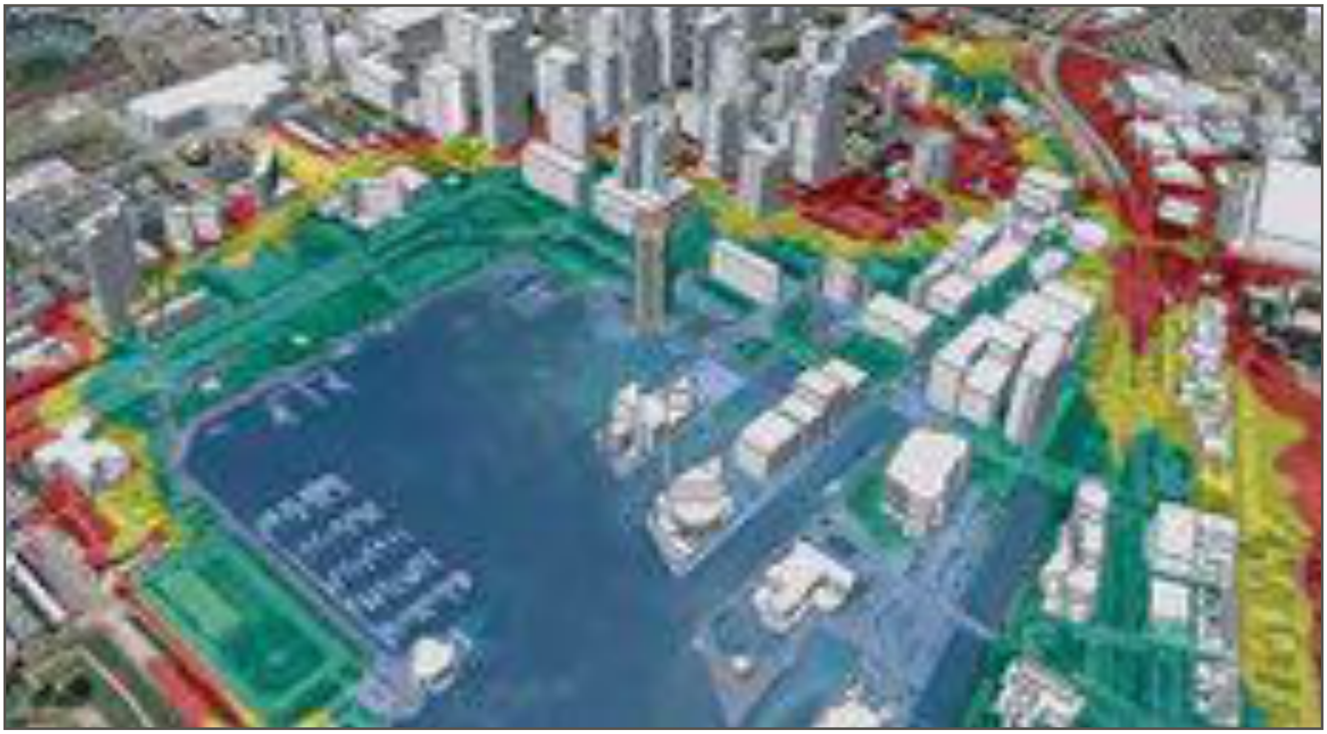


Figure 3–5 Baltimore City Flood Hazard Areas Showing 3ft, 5ft, and 7ft Sea Level Rise Scenarios



Storm Surge Modeling *Source: USACE*

Sea Level Rise

For a number of reasons — including climate change and an anticipated increase in global temperature — the world's sea levels have been rising in the past 100 years. In Baltimore, NOAA sea level gauges at Fort McHenry, as well as other official reports, have shown that relative sea level in the Harbor area has increased by 12 inches since 1900. The most current sea level data from the Maryland State Climate Change Commission, and from the Intergovernmental Panel on Climate Change, indicate that sea levels in the Baltimore region could experience an additional rise of 1.5 to 3 feet in the next 50 years. Approximately 1.33 percent of Baltimore City land is within the projected sea level rise zone.[10]

Projections for global increases in sea level range from less than 1 foot for lower emissions scenarios to as much as 1.6 feet for higher emissions scenarios by the middle of the century. By 2100, these projections swell to between 1.7 and 4.6 feet. In Maryland, relative sea-level rise projections range from 0.9 to 2.1 feet by 2050 and 2.1 to 5.7 feet by 2100.[11] In fact, recent findings reveal that sea level rise is accelerating faster than previously projected due to rapid polar ice sheet melting. In particular, sea level rise has also been greater than anticipated along Mid-Atlantic coastlines, where the waters rise as the flow of Gulf Stream slows.[12]

Although relative seal level rise is a gradual process, Baltimore City may still experience acute impacts in the near term. Some examples include increased frequency of low-level inundation, storm-exacerbated floodwater rise that coincide with high tides or astronomical-influenced tides, increasing rates of coastal erosion in non-bulk-headed areas, and increased saltwater intrusion into underground utilities and infrastructure. Furthermore, scientists recommend planning for the higher range of projection values so as to take into account increased risks associated with flooding during storms.

When the temporal factor of sea level rise is coupled with the relative increase in land-falling the potential for tropical systems to cause extreme tidal flooding will increase. Baltimore's waterfront is densely developed and will continue to have development pressure for the foreseeable future. Coastal storm surges may be amplified by sea level rise, creating a greater threat. Figure 3–5 Baltimore City Flood Hazard Areas Showing 3ft, 5ft, and 7ft Sea Level Rise Scenarios, delineates the potential impact for a 100- or 500-year storm when accompanied with sea level rise (showing 3ft, 5ft, and 7ft SLR scenarios). This will impact current and future shoreline development. The impacts of rising sea level on Baltimore City will continue to present significant short- and long-term challenges to its waterfront communities.

Tsunami in Japan, 2011 *Source: telegraph.co.uk*

Tsunamis

As stated in the 2011 Maryland State Hazard Mitigation Plan (HMP) "A tsunami is a series of sea waves caused by the displacement of a large volume or body of water. Tsunamis may result from local or distant large-scale seafloor displacement, including seismic activity, volcanic activity or landslides that generate uplift or drop in the ocean floor." [13]

"Waves travel in all directions from the originating tsunami sources, building in height as the wave approaches the shore. The topography and geometry of the coastline, wave direction or path, and offshore topography influence the run-up (or terminal height) of the wave and therefore potential for damage."[14]

While the focus of hazard identification and mitigation planning in this document has centered on atmospheric- and surface-related natural hazards, recent oceanic events have introduced new concerns regarding potential vulnerability of coastal areas such as Baltimore to unusual hazards such as Tsunamis. This section will summarize existing analysis presented in the Maryland State Hazard Mitigation Plan regarding Tsunami risk, as well as discuss recent scientific research on potential risks and causes of East coast Tsunami events. A 2002 Tsunami Hazard Assessment by the National Geophysical Data Center concluded that "There is a substantial danger of tsunamis along the East Coast of the United States that may have been underestimated previously."[15]

On June 13, 2013, portions of the New Jersey coastline, recently ravaged by a 13-foot high storm surge from Hurricane Sandy in October 2012, experienced a Tsunami. Observers and local news media reported that on the afternoon of 6/13, the water level along the coast in central New Jersey rapidly rose as much as 6 feet in a matter of a few minutes.

This rare event was reported in local media and later examined closely by NOAA meteorologists and other scientists. NOAA later classified the event as a "meteo-tsunami" in a July 2013 report, stating

> *"Tsunami-like waves were observed along the US east coast during the afternoon of Thursday, June 13, 2013. Over 30 tide gages recorded the fluctuations with impacts noted along the New Jersey shore and in Massachusetts. In Barnegat Light, NJ,* ***at least two people were swept off a breakwater and required medical treatment****. The NOAA meteorologist from the JPWTS reported in the official account that "The event occurred in close conjunction with a strong weather system moving from west to east off the New Jersey coast which is labeled by the NWS as a low-end derecho."*

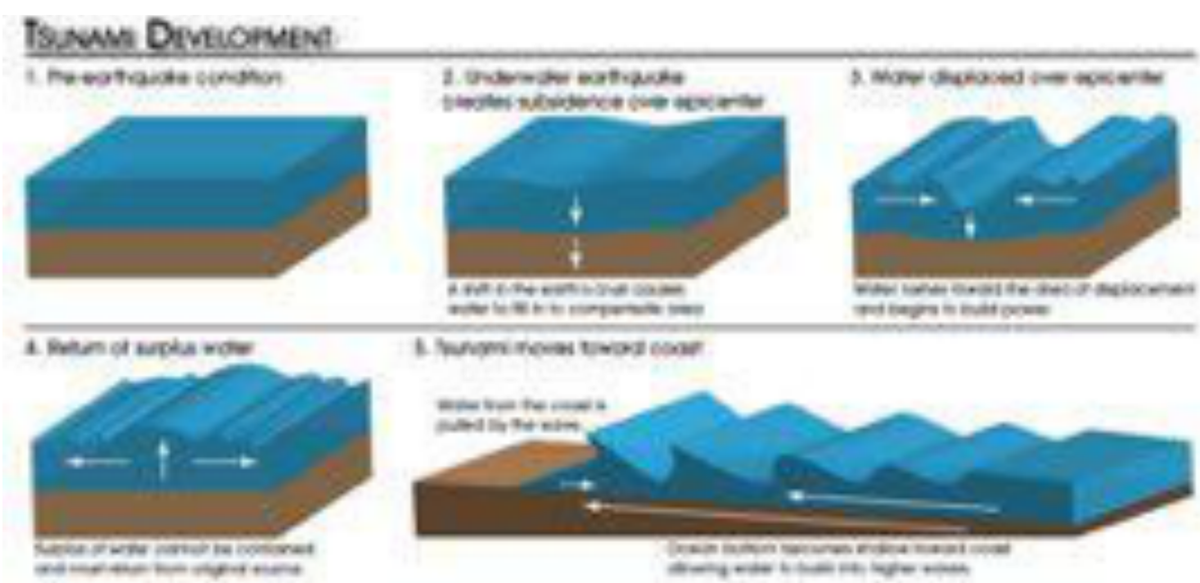
While a tsunami is traditionally caused by geological forces such as undersea landslides, earthquakes, volcanoes or other seismic influences, this occurrence could be considered an example of a "geo-atmospheric" type event that upon closer investigation, could present a significant new hazard planning concern for vulnerable high population areas such as Baltimore City and surrounding areas. This potential new hazard is being considered by the Disaster Preparedness and Planning Project Committee due to the concerns that;

1) A "meteo-tsunami" or similar wave-event could occur in the Chesapeake Bay at a critical time when large numbers of people are assembled near the water;
2) Policy-makers and infrastructure planners alike may need to make considerations for additional resiliency to no-notice coastal flooding in new construction as part of on-going coastal hazard mitigation strategies;
3) Geological research suggests that many areas of the continental shelf in proximity to the mouth of the Chesapeake may contain at-risk regions which can produce undersea landslides.

The 2011 Maryland State HMP denotes three primary causations of East coast tsunamis: "Inundation (the extent the water goes over the land), wave impact (from incoming and receding currents) and coastal erosion. While most tsunamis occur in the Pacific Ocean, which consists of subduction zones where vertical plate movement results in earthquakes. Conversely, the U.S. East Coast has been, until recently, considered in an area with reduced threat from tsunamis.

Among the potential causes of a significant tsunami event along the U.S. East Coast, and particularly the Mid-Atlantic, this report assesses the relative probability of different events pertaining to Baltimore:

- Tectonic activity: In the Atlantic Ocean, the Mid-Atlantic Ridge is a spreading center (a divergent plate boundary). The U.S. East Coast is a passive margin, characterized by minimal tectonic activity and a low sloping continental shelf. The majority of the Atlantic Ocean's tectonically active areas (seismic and volcanic) are concentrated near the Caribbean Islands and at the Scotia island arc chain. (MD HMP) For Baltimore, this tsunami causation is considered at the lowest probability.
- Volcanic, Subsurface or Meteoric: Other eastern seaboard tsunami sources include volcanic debris falls or catastrophic failure of volcanic slopes, explosive decompression of underwater methane deposits or oceanic meteor splashdowns such as the Chesapeake Bay Bolide which is believed to have produced a crater at the mouth of today's Bay. Peer-reviewed research in Geologic journals regarding methane deposits suggests this tsunami causation is still generally low probability, but a rising concern among oceanographers.
- Slumping and Submarine Landslides: Since subduction zones are absent around most of the Atlantic basin, tsunamis and tsunami-like waves along the U.S. East Coast are generally the result of slumping or landsliding associated with local earthquakes or with wave action associated with strong storms. In the past century, "no-notice" submarine landslide induced tsunamis have shown to produce damage to coastal areas of the Eastern U.S., Bermuda and the Caribbean. This observation places a higher hazard probability for Baltimore.



Tsunami Development *Source: Cameron Dougals Craig, 2011*

Overview of historical Tsunami events from the 2011 Maryland HMP which have occurred in the Atlantic Ocean basin and affected the U.S. East coast, including the Mid-Atlantic region include:

- Earthquakes in the Azores-Gibraltar convergence zone (e.g., Lisbon earthquake in 1755);
- Earthquakes along the Hispaniola-Puerto Rico-Lesser Antilles (Caribbean) subduction zone, in and around the Puerto Rico Trench or near the Leeward Islands;
- Large mass failure event, including the potential flank collapse of the Cumbre Vieja;
- Volcano in the Canary Islands;
- Landslide tsunamis caused by Submarine Mass Failures (SMF) triggered along the East coast continental slope by moderate seismic activity. Significant geological and historical evidence (e.g., the 1929 Grand Bank landslide tsunami and the Currituck Slide off North Carolina and Virginia) suggests that SMF tsunamis pose the most significant tsunami hazard to the upper east coast, triggered on the continental slope by moderate seismic activity (magnitude 6.0 to 7.5).

Hurricane Isabel, September 18, 2003 *Source: NASA*

"Although such near-field landslide tsunami sources are less energetic than co-seismic (e.g. earthquake induced) tsunamis, SMFs can occur at a shorter distance from shore and therefore cause significant run-up on small sections of the coast while offering little warning time, thus posing significant hazard to local, low-lying, coastal communities, such as Ocean City, MD and Worcester County. For example, SMFs with volumes of above 100 km3 can generate vertical extent of wave uprush on a beach or structure (run-up) of more than two meters."

While two of the three primary causes of Tsunamis are generally considered extremely low-probability events, the 2011 Maryland Plan outlined one particular scenario that could present a significant long term Tsunami hazard to Baltimore, as well as this hazard being counted in the "no-notice" category like that of derechos and other severe weather events. Among the two areas of highest concern for potentially high-impact tsunami events that could affect Baltimore include two East Coast off-shore areas currently being investigated for potential future large-scale submarine slope failure. These sites include:

- Large cracks discovered northeast of Cape Hatteras (off the coast of North Carolina and Virginia). The cracks are located on the outer shelf edge and exist as a series of "en echelon cracks" (Maryland HMP Figure 3-43).
- Submarine canyons located approximately 150 kilometers east of Atlantic City, New Jersey.

The North Carolina-Virginia site also contains evidence of a large submarine landslide, the Albemarle-Currituck Slide, which has been dated to approximately 18,000 years ago, with over 33 mi of material, moved seaward from the continental shelf, most likely causing a tsunami. These cracks may indicate a progression in slope failure and the potential for another submarine landslide to occur that could trigger a tsunami on the order of a few to several meters in height, similar to a storm surge resulting from a Category 3 or 4 Hurricane. Further, investigations suggest that the cracks are in areas of large deposits of methane hydrate and pressurized water, wherein sudden release of the water or methane may have produced the cracks and slope failure. (MD HMP)

Given the existing vulnerabilities of Baltimore City's coastal infrastructure and sensitive populations, this Tsunami Hazard Assessment was included to provide a starting point for future examination of appropriate preparatory and mitigation measures which can be undertaken as the City's plans develop.

Flooding from heavy precipitation shuts down a portion of the Jones Falls Expressway *Source: Baltimore Sun*

Precipitation Variability

The amount of precipitation that falls over an area will vary by large amounts as global temperatures increase. Precipitation events are likely to increase in magnitude in Baltimore City leading to increased flash flooding. Among the many harmful effects of climate change, increased stormwater runoff and demand for stormwater management are anticipated to be some of the greatest challenges facing cities.[16] Climate projections for the State of Maryland predict that the average annual precipitation will increase between 5-12 percent by the end of the century.[17] In Baltimore, studies suggest that precipitation could increase by as much as 227mm each year by the middle of the century.[18] At the same time, the Northeast Region is expected to experience more frequent heavy precipitation events — where more than 2 inches of rain falls within a 48 hour time period — while the intensity of heavy precipitation events is projected to increase by 12-15 percent.[19]

Most of Maryland's precipitation falls in the summer months but winter precipitation is expected to rise and the form of this precipitation is likely to be altered. While temperatures increase, more rain will fall in Maryland's winter months, with a projected 50 percent decrease in snow volume by the end of the century.[20] As precipitation frequency and intensity will increase, Baltimore will be more vulnerable to flash flooding events.

Heavy precipitation may, at times, be conveyed through what scientists refer to as "atmospheric rivers." These channels carry immense quantities of water across the planet, and contribute to the intensity of heavy precipitation events. Atmospheric rivers may cause both rainstorms and snowstorms. For instance, an atmospheric river was responsible for the "Snowmageddon" event that hit Baltimore in 2010.[21] Even more alarming, atmospheric rivers are likely to become stronger due to a warming planet and higher saturation levels of water vapor in the atmosphere. This increase could lead to an increase in both severity and frequency of rain- or snowfall, and contribute to significant flooding and other damage.

Thunderstorms

When atmospheric conditions combine to provide moisture, lift, and warm unstable air that rapidly elevates, a thunderstorm is formed. Thunderstorms can occur at any time of day and in all months of the year, but are most common during summer afternoons or evenings and in combination with frontal boundaries. Maryland experiences approximately 20-40 thunderstorm days per year and frequently occur in Baltimore. Thunderstorms are considered a significant hazard due to their ability to spawn tornadoes, hailstorms, strong winds, flash floods, and damaging lightning.

Table 3–16 Thunderstorm Property Damage 1956-2010	
Property Damage (Total)	Property Damage (Annualized)
$49,257	$896
Source: Table 3-66, Maryland Emergency Management Agency, 2011: 180.	

Table 3–17 Thunderstorm Injuries and Deaths 1956-2010		
County/City	Total Injuries	Total Deaths
Baltimore City	1	2
Source: Table 3-65, Maryland Emergency Management Agency, 2011: 179.		

Severe thunderstorms have varied characteristics and can inflict considerable damage. The National Weather Service classifies a thunderstorm as severe if it produces hail that measures at least one inch in diameter, winds of 58 mph or greater, or a tornado. Thunderstorms affect a smaller area compared with winter storms or hurricanes, but for a number of reasons, can be dangerous and destructive. Storms can form in less than 30 minutes, giving very little warning and can cause considerable damage.

Table 3–16 Thunderstorm Property Damage 1956-2010, notes measured economic costs and damage associated with thunderstorm events in Baltimore City from 1956 to 2010. In that time period, thunderstorms had been responsible for $896 in property damage annually. In that same period, thunderstorms in Baltimore City had killed two individuals (Table 3–17 Thunderstorm Injuries and Deaths 1956-2010).

Lightning striking the World Trade Center building in downtown Baltimore *Source: Flickr.com*

Table 3–18 Damage from Hail in Baltimore, 1950 to 2012					
Date	Time	Size (Inches)	Injuries	Fatalities	$ Loss (Millions)
8/12/1957	13:30:00	0.75	0	0	0
8/1/1963	16:00:00	1	0	0	0
6/18/1970	16:10:00	4.5	0	0	0
5/25/1979	18:10:00	1.75	0	0	0
4/24/1991	11:30:00	1	0	0	0
4/24/1991	11:52:00	1	0	0	0
11/8/1996	14:40:00	0.75	0	0	0
6/2/1998	17:29:00	1.75	0	0	0.005
7/30/1999	18:50:00	1.75	0	0	0
5/13/2000	14:40:00	1	0	0	0
7/14/2000	16:15:00	1.75	0	0	0
5/2/2002	14:10:00	1	0	0	0
5/13/2002	13:35:00	1	0	0	0
4/3/2006	17:50:00	0.75	0	0	0
7/10/2007	11:45:00	1	0	0	0
8/14/2012	20:07:00	1	0	0	0

Lightning

Every thunderstorm is accompanied by lightning; in fact, the actual sound of thunder is a direct result of lightning. The phenomenon occurs when water droplets are carried by the updraft of a thunderstorm to the upper parts of the atmosphere where they freeze and become charged. Lightning is the charged electrical channel that shoots downward toward the earth's surface. As this channel nears the ground, it is attracted to oppositely-charged channels which, once connected, create a powerful electrical current that produces a visible flash of lightning.

Lightning often strikes outside of areas where rain is actually falling, at times appearing as far as 10 miles away from rainfall. It can strike from any part of the storm, and may even strike after the storm has seemed to pass. Additionally, a lightning bolt can warm the surrounding air to temperatures as high as 60,000° Fahrenheit.[22] In Baltimore, lightning strikes have been the cause of significant property damage throughout the years, and have even taken the lives of City residents. As the frequency and intensity thunderstorms increases, so will the lightning associated with these storms.

Hail

Hail is another dangerous by-product of severe thunderstorms. Hail is formed in towering cumulonimbus clouds (thunderheads) when strong updrafts carry water droplets to a height at which they freeze. Eventually, these ice particles become too heavy for the updraft to support and they fall to the ground at speeds of up to 120 mph. When falling at such high speeds, the hail has insufficient time to melt in the warmer air and reaches the ground in the form of ice.

Hail falls along paths called swaths, which can vary from a few square acres to up to 10 miles wide and 100 miles long.[23] Hail larger than ¾ inch in diameter can inflict great damage to both property and crops. Some storms produce hail over 2 inches in diameter. In Baltimore, the largest size hail measured between 1950 and 2012 had been 1.75 (Table 3–18 Damage from Hail in Baltimore, 1950 to 2012). Although hail in Baltimore had not caused significant economic losses during this period, hail causes about $1 billion in damages annually in the U.S. Hail is already a known occurrence in Baltimore. Though climate scientists predict more frequent and intense severe storms in the future, it is difficult at this point to establish any long-range projections regarding the future impact of hail in Baltimore.

A Scene from Baltimore following a wave of heavy storms, dubbed "Snowmageddon" *Source: Baltimore Sun*

Winter Storms and Climate Influences

Winter storms produce more than just snow. Winter weather can take many forms, including freezing rain, sleet, extreme cold and high winds. These conditions may occur singly or in any combination. Freezing rain is that which falls onto a surface where the temperature is below freezing, causing the rain to form a coating of ice. Conversely, sleet occurs as rain drops freeze into ice pellets in the cold air before reaching the ground. Like snow, freezing rain and sleet can create hazardous conditions for motorists. Even small accumulations of ice can make walking or driving extremely dangerous. Moreover, significant accumulations of ice can fell trees and utility lines, resulting in loss of power and communication.

Regarding winter weather projections, the noticeable uptick in major winter storm events in Baltimore since 1996 has been compared to the relatively snowy periods in the 1950's and 1960's. This suggests that although climate change has influenced average temperatures, it is also possible that the Baltimore region could experience increased precipitation in the form of snowfall due to increased moisture content driven by rising evaporation from warmer bodies of water. An April 2013 journal article from the Bulletin of the American Meteorological Society, titled *Monitoring and Understanding Trends in Extreme Storms* noted that "observed increases in extreme precipitation are "consistent with the observed increases in atmospheric water vapor, which have been associated with human-induced increases in greenhouse gases."[24] The article also points to findings relevant to concerns for Baltimore City's unique weather in recent years that "while the role of water vapor as a primary cause for the increase in extreme precipitation events is compelling, the possibility of changes in the characteristics of meteorological systems cannot be ruled out. There may also be regional influences from the temporal redistribution of the number of El Niño events versus La Nina events and from land use changes."

Table 3–20 Winter Storms and Freezes, notes severe winter storm events (storms and freezes) in Baltimore that caused considerable damage. The public sector cost of a blizzard in 1996, for instance, totaled $20 million in Maryland. Winter storm warnings are issued when snowfall is expected to accumulate more than 4 inches within 12 hours, or when a quarter of an inch or more of freezing rain will accumulate. Severe winter storms can significantly slow traffic, decrease commercial activity, lead to power outages, disrupt communications, and even force vulnerable buildings to collapse.

While winter storms are expected in Baltimore — and the City budgets and prepares for snow removal activities each year — winter storms occasionally reach a magnitude that overwhelms local response efforts. This stress may be placed on the transportation system as roads are unable to be efficiently salted or plowed, or it may be placed on electrical infrastructure. As a result of a 1994 ice and sleet storm, for example, the City of Baltimore experienced power and phone line outages, as well as rolling blackouts, due to increased use of electricity and natural gas. Some residents were left without power or heat for nearly two weeks.

Over the past decade, Baltimore City has experienced several strong winter storms that have disrupted regular activities and caused a number of automobile accidents and power outages. Climate averages for Baltimore denote 21.1 inches of snowfall annually for any given year. Table 3–19 Significant Winter Storms in Baltimore, MD, shows significant winter storms during which the region received more than the annual snowfall in a single snow event.

Years that bring several winter storms, frequent episodes of disruptive precipitation or extreme cold can tax the energy supply, raising the cost of heating homes, businesses and public facilities. In 2010, two severe winter storms took place just days apart. Following the 25 inches of snow that had fallen on February 5th, a second snowstorm on February 9, 2010, brought an additional 19.5 inches of snow, negatively impacting critical emergency facilities. Together, public sector cost for these two storms totaled nearly $35 million for the City of Baltimore alone.

Table 3–19 Significant Winter Storms in Baltimore, MD

Date	Inches of Snow and Ice
March 15-18, 1892	16.0 inches
February 12-14, 1899	21.3 inches
February 16-18, 1900	12.0 inches
January 27-29, 1922	26.5 inches
March 29-30, 1942	22.0 inches
February 15-16, 1958	15.5 inches
December 11-12, 1960	14.1 inches
March 5-7, 1962	13.0 inches
January 30-31, 1966	12.1 inches
February 18-19, 1979	20.0 inches
February 11-12, 1983	22.8 inches
January 22, 1987	12.3 inches
January 7-9, 1996	26.6 inches
January 25, 2000	14.9 inches
February 16-18, 2003	26.8 inches
December 18, 2009	18 Inches
February 5-6, 2010	25-29 Inches
February 9-10, 2010	19.5 inches

National Weather Service, www.nws.noaa.gov/er/lwx/winter/storm%2Dpr.htm

While major snow and ice storms may appear to be on the rise in the short term, according to the Intergovernmental Panel on Climate Change 2007 Fourth Assessment Report (AR4), a factor which may be driving this observation is an actual decrease in global snow and ice cover. The IPCC noted in AR4 that "observations show a global-scale decline of snow and ice over many years, especially since 1980 and increasing during the past decade, despite growth in some places and little change in others."[25]

While "most mountain glaciers are getting smaller, and snow cover is retreating earlier in the spring, Sea ice in the Arctic is shrinking in all seasons, most dramatically in summer."[26] The report notes that important coastal regions of the ice sheets are thinning in places like Greenland and West Antarctica, which is contributing to a sea level rise of at least 1.2mm globally just in the 10-year period between 1993 to 2003.

For Baltimore, the contrasting reduction in snow-cover and sea ice has been identified as an influential factor in altering weather patterns over the Northern Hemisphere. This climate contrast has produced extreme cold and snow in some regions — such as central and northern Europe from 2012 to 2013 — while leaving other regions, including the Mid-Atlantic in the U.S., with highly variable snowfall and winter temperatures from year to year. As average annual temperatures increase overall, winter temperatures will likewise become warmer. While winter temperatures have only slightly increased in Baltimore in recent decades, temperatures are projected to increase between 4-7° by 2025. Carrying this projection forward, winter temperatures could be an estimated 7.4-10.6° warmer by the end of the century.[27] For this reason, and due to high fluctuations in winter weather impacts, many eastern U.S. cities, including Baltimore, are actively preparing for winter extremes.

Winter storms may also significantly disrupt the ability of Baltimore residents to go about completing daily routines. Populations who are less mobile, or who have chronic illnesses or age-related limitations, are most vulnerable. For these residents, snow and ice will pose additional health hazards, including heart attacks from physical exertion after clearing a sidewalk of snow; inability to access vital medical services; or being trapped indoors.

Table 3–20 Winter Storms and Freezes

Date of Storm	Storm Type	Severity at Impact	Damages	Recovery Time	Public Sector Cost	Facilities Impacted	Historical Elements Impacted
2/11/1983	Snow Storm	22.8 inches					
2/10/1994	Ice and Sleet	3 inches of freezing rain/ice -28 degree wind chills 40+ MPH wind		People without power and heat for nearly 2 weeks			
1/8/1996	Blizzard of '96	26.6 inches			$20 million in Maryland		
1/25/2000 to 1/30/2000	Severe Winter Storms	14.9 inches	Rolling blackouts due to increased use of electricity and natural gas; tree loss due to heavy ice; power and phone line outages; Car accidents				
2/15/2003 to 2/18/2003	Severe snowfall	28.2 inches			$3,000,000		Roof collapse of B&O Railroad Museum
2/11/2006 to 2/12/2006	Snow Storm	13.1 inches	62,000+ People Lost Power				
12/18/2009	Snow Storm	18 inches			$2,191,670 (Baltimore)		
2/5/2010	Severe winter storm	25.0 inches	34,000 BGE Customers without power (region)		$34,783,976 (Baltimore)	Harbor Hospital, Oldtown Station, BPD Southern District, Stratford water pump station lost power	
2/9/2010	Severe winter storm	19.5 inches					
1/26/2011	Snow Storm	9.8 inches	Car accidents; JFX gridlocked; vehicles abandoned on roadways; 122,000 BGE Customers without power			3800 E. Biddle (garage), 6400 Pulaski Hwy (plow shop), 239 N. Calverton (substation)	

Nor'Easters

Some of the most significant winter storms that affect Maryland are known as "Nor'easters" because they are accompanied by strong northeast winds. These storms often form in the Gulf of Mexico, intensify, and then move up the East Coast. High pressure systems over the Maritime Provinces of Canada deliver the cold air to Nor'easters that result in winter precipitation. The cold air flowing from the north forms what actually looks like a wedge, bounded on the west by the mountains of Washington and Allegany Counties and by warmer winds coming off the Atlantic Ocean on the east. Meteorologists call this the "cold air dam" or "the damming effect." Moist air coming from the south flows up over this dam, producing heavy winter precipitation.

Often, the heaviest snow with a Nor'easter occurs in a band 50 to 100 miles wide, usually setting up over central or eastern areas of Maryland. Precipitation along this band typically changes from snow in the west, to a transition area of freezing rain and sleet, then finally to rain in the east. Areas receiving mostly snowfall can experience totals of greater than a foot of precipitation. In the most intense Nor'easters, thunder and lightning may also be observed. The distribution, intensity and type of precipitation associated with Nor'easters are highly dependent on the track of the center of the storm system. A system that tracks nearest the coast is more likely to produce rain along the coast and snowfall further inland. A system that tracks a bit further out to sea is more likely to produce mostly snowfall even along the coast.

Winter storms can also be life threatening events. From reports measured between 1993 and 2010, Winter Storms accounted for a total of 8 deaths and 166 injuries in Baltimore City (Table 3–21 Winter Storm Hazard - Injuries and Deaths).

Table 3–21 Winter Storm Hazard - Injuries and Deaths

County/City	Total Injuries	Total Deaths
Baltimore City	166	8

Source: Table 3-76, Maryland Emergency Management Agency, 2011: 204.

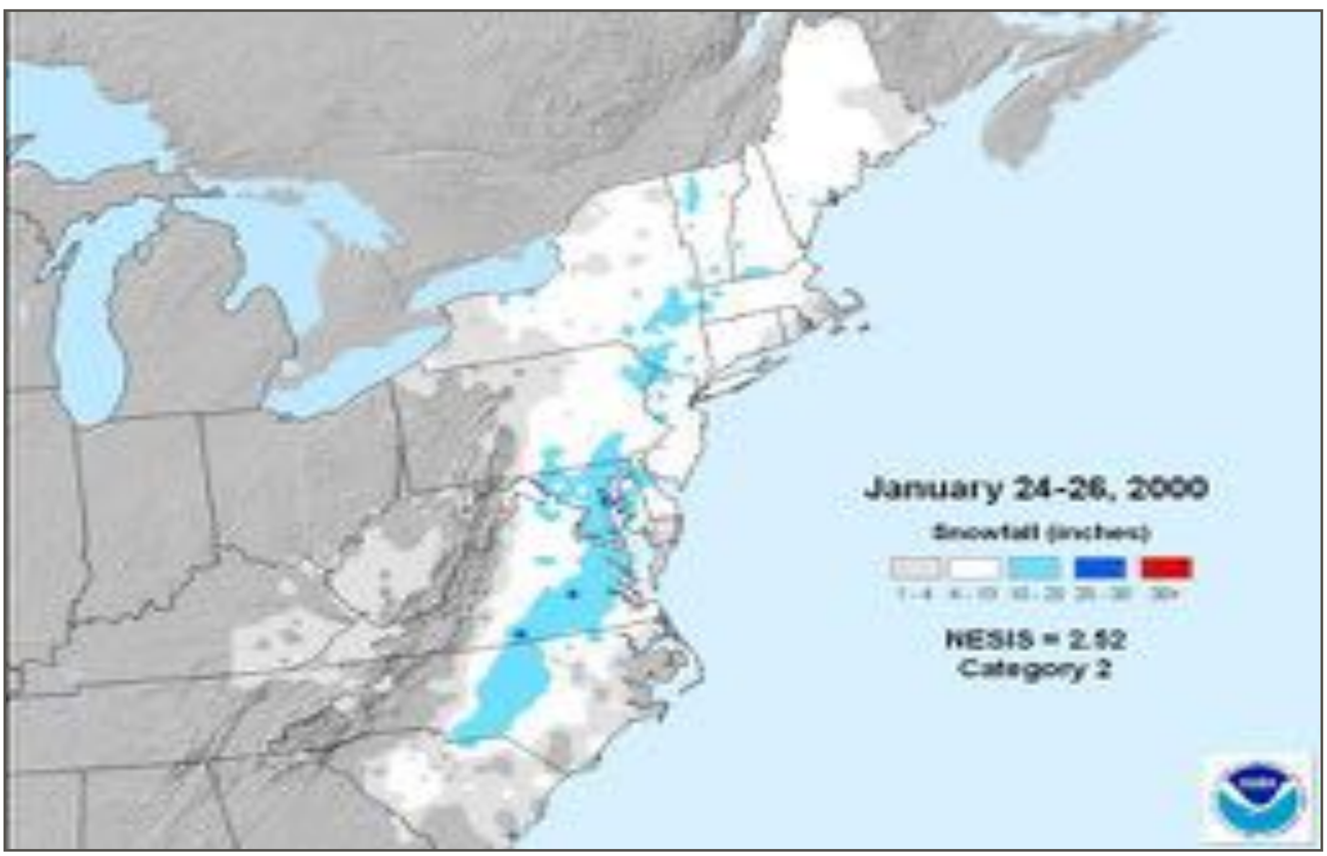


Figure 4–6 Map Showing January 2000 Nor'Easter *Source: NASA*

Pretty Boy Reservoir during the drought of 2002 *Source: gunpowderfalls.org*

Drought

Droughts are extended periods of dry weather, caused by a natural reduction in the amount of precipitation over an extended period of time. Droughts may be classified as meteorological, hydrologic, agricultural, or socioeconomic events. Table 3–22 Drought Classification Definitions presents definitions for these different types of droughts:

Table 3–22 Drought Classification Definitions

Type	Definition
Meteorological	The degree of dryness or departure of actual precipitation from an expected average or normal amount based on monthly, seasonal, or annual time scales.
Hydrologic	The effects of precipitation shortfalls on streamflows and reservoir, lake, and groundwater levels.
Agricultural	Soil moisture deficiencies relative to water demands of plant life, usually crops
Socioeconomic	The effect of demands for water exceeding the supply as a result of a weather-related supply shortfall.

Multi-Hazard Identification and Risk Assessment, FEMA

While occurring less frequently in Baltimore City than in surrounding jurisdictions, meteorological and hydrologic droughts are natural hazards that present major threats to the City and regional water supply. Such droughts may ultimately evolve into socioeconomic droughts in which the City's ability to deliver water to residents or businesses becomes limited. Additionally, Baltimore provides public water to areas outside of the City's boundaries; therefore, a drought may greatly diminish water supplies that are available not only to the City of Baltimore, but also to the surrounding counties.

Droughts may vary greatly in their extent, duration, severity, and impact. Their conditions may be worsened by human activities, high temperatures, high winds, and low humidity. To mitigate the intensity of a drought's effects, the City may be forced to impose water rationing requirements upon households. This form of restriction has only been applied once in recent years; however, limits on car washing or other commercial/institutional uses have been more common. Such restrictions can have a negative economic impact on water-dependent businesses. During a prolonged drought event, land values can decrease, unemployment can increase, and certain industries or individuals may be impacted more than others. The agriculture industry, for instance, generally experiences the first and harshest effects of droughts (for a more detailed discussion about agriculture, see Extreme Heat Hazard Profile).

Pretty Boy Reservoir during the drought of 2002 *Source: USGS*

A listing of significant Maryland droughts is presented in Table 3–23 Historical Droughts in Maryland. For each dry period, the table the region that had been affected, and notes the economic cost for two of the events. A drought recurrence interval is the average interval of time within which streamflow would be less than usual during a drought event. The U.S. Geological Survey (USGS) is able to determine annual departures from average streamflow and assign recurrence intervals to each drought. For Baltimore, the USGS identified five regional droughts which had significant extent and duration: (1) 1930 to 1932; (2) 1953 to 1956; (3) 1958 to 1971; (4) 1980 to 1983; and (5) 1984 to 1988. The drought from 1930 to 1932 was likely the most severe agricultural drought ever recorded in Maryland. Rainfall during that period was approximately 40 percent less than average, and 1930 was the driest year recorded since 1869. Total cost of crop losses during 1930 were estimated at $40 million in the region.[28]

Since 1930, droughts have occurred about once every 10 years, with mixed severity and duration. Recurrence intervals during the drought from 1953 to 1956 had generally been 10 to 25 years — with the exception of areas north and east of Baltimore, where recurrence intervals were less than 10 years. From 1958 through 1971, a 13-year regional drought with recurrence intervals greater than 25 years caused severe streamflow deficiencies throughout Maryland.

Table 3–23 Historical Droughts in Maryland

Dates	Area Affected	Economic Cost
1930-1932	Regional	$40,000,000 in crop losses (1930)
1953-1956	Regional	
1958-1971	Regional	
1980-1983	Multi-State	
1984-1988	East MD	$302,000,000 in estimated agricultural losses (1986-1988)
2002	Central MD	

Greatly exceeding regional losses during the 1930 drought, the 1986 to 1988 drought accounted for an estimated loss of $302 million.

While long-term or water-supply droughts — where rainfall deficits of more than 14 inches persist for two years or more — currently occur less than 4 percent of the time in Maryland, that percentage is expected to increase to approximately 5 percent by the end of the century. Furthermore, the duration of annual dry spells in Maryland is projected to increase from the current average of 15 days to as many as 17 days.[29]

Windy commute challenges residents during the 2012 Northeast blizzard *Source: Brian Snyder*

Wind

Wind is the motion of air past a given point caused by a difference in pressure from one place to another. Wind poses a threat to Maryland in many forms, including winds that are produced by severe thunderstorms and tropical weather systems. The effects of wind can include blowing debris, interruptions in elevated power and communications utilities, and intensified effects of winter weather. Harm to people and animals, as well as damage to property and infrastructure, may result.

In the mainland United States, mean annual wind speed is reported to be 8–12 mph, with frequent speeds of 50 mph and occasional wind speeds greater than 70 mph. In coastal areas, from Texas to Maine, tropical cyclone winds may exceed 100 mph. In the mid-Atlantic, high wind speeds are generally produced by severe thunderstorms and tropical storms/hurricanes. The most severe windstorms may produce tornadoes.[30]

Table 3–24 Wind Events in Baltimore, 1950 to 2012

Total Wind Events	Average Windspeed	Total Cost of Damage (Millions)	Average Cost of Damage (Millions)
116	29.8793	25.3715	0.2187198

Windstorms also have the capacity to cause considerable personal and property damage. From records of 116 high wind events measured between 1950 and 2012 (Table 3–24), the average wind speed was approximately 30 mph, at times reaching speeds of 78 mph. Fortunately, these events did not cause any fatalities in Baltimore; however, 21 injuries were recorded. Additionally, total recorded property damage exceeded $25 million, with an average of nearly $220,000 in damage for each event.

Destruction of trees and other vegetation may produce secondary impacts that damage structures and power lines, or block roadways and storm drainage systems. For instance, downed trees may topple power lines or cause property damage if they fall. Minor structural damage —to shingles, gutters, etc. — may also be sustained by some. Measured between 1956 and 2010, Baltimore City reported a total of 30 wind related injuries (Table 3–25). During the same time period, property damage from wind events totaled an average of $15,601 a year (Table 3–26).

Table 3–25 Wind related injuries and deaths per county, 1956-2010

County/City	Total Injuries	Total Deaths
Baltimore City	30	0

Source: Table 3-56, Maryland Emergency Management Agency, 2011: 168.

Figure 3–8 Map Showing Wind Speed During Hurricane Sandy

Table 3–26 Wind crop and property damages per county, 1956-2010

Property Damage (Total)	Property Damage (Annualized)	Crop Damage (Total)	Crop Damage (Annualized)	Total Damage	Total Damage (Annualized)
$858,078	$15,601	$ 1	$ -	$858,079	$15,601

Source: Table 3-60, Maryland Emergency Management Agency, 2011: 171.

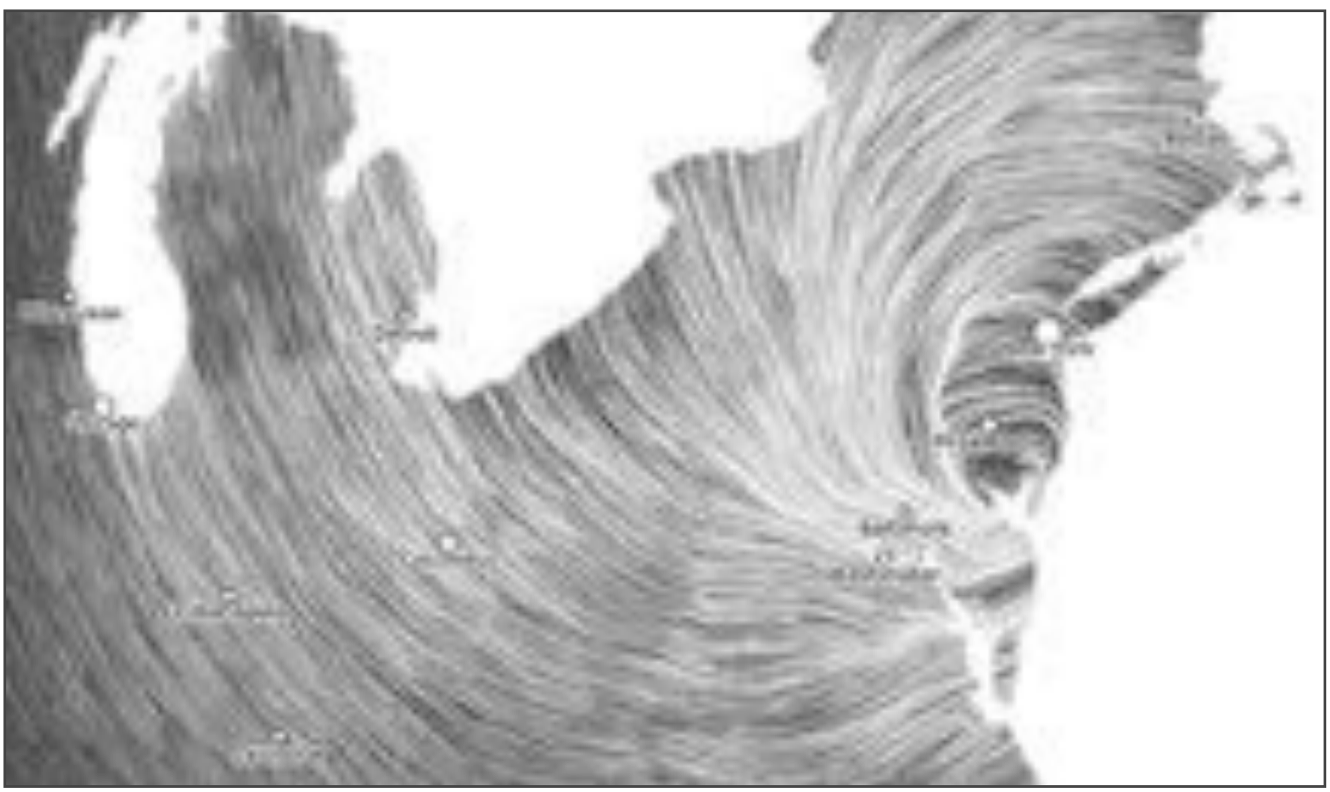


Figure 3–7 Map Showing Wind Direction During Hurricane Sandy

Tornados

A tornado is a violent atmospheric disturbance characterized by one or more twisting and funnel-shaped columns, extending from a thunderstorm cloud toward the ground. Tornadoes can touch the ground with winds over 300 mph. While relatively short-lived, tornadoes are intensely focused and are one of nature's most violent storms.

Tornadoes are measured according to their wind speed on the Fujita Scale (F-Scale). Revised in January of 2007, the Enhanced Fujita Scale, illustrated in Table 3–27 Enhanced Fujita Tornado Intensity Scale, below, ranges from an EF0 to an EF5. The strongest tornadoes ever observed have produced winds over 200 mph. Different wind speeds may cause similar-looking damage from place to place or from building to building. Without a thorough engineering analysis of tornado damage in any event, the amount of damage from any given storm may be unpredictable.

Spawned by powerful thunderstorms or hurricanes, tornadoes are produced when a southwesterly flow of warm, moist air combines with both northwesterly and southwesterly flows of cool and dry air, thereby forcing the warm air to rise rapidly. Most damage results from high wind velocity and wind-blown debris. Tornadoes may range from just several yards to over two miles in width; and, although tornadoes normally only travel on the ground for short distances, tornado tracks of 200 miles or more have been reported.

Table 3–27 Enhanced Fujita Tornado Intensity Scale

Category	Wind Speed	Examples of Possible Damage
EF0	Gale Tornado (65 – 85 mph)	**Light damage**. Some damage to chimneys; break branches off trees; push over shallow-rooted trees; damage to sign boards.
EF1	Moderate Tornado (86 – 110 mph)	**Moderate damage**. The lower limit is the beginning of hurricane wind speed; peel surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off roads.
EF2	Significant Tornado (111 – 135 mph)	**Considerable damage**. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated.
EF3	Severe Tornado (136 – 165 mph)	**Severe damage**. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; cars lifted off ground and thrown.
EF4	Devastating Tornado (166 – 200 mph)	**Devastating damage**. Well-constructed houses leveled; structure with weak foundation blown off some distance; cars thrown and large missiles generated.
EF5	Incredible Tornado (over 200 mph)	**Incredible damage**. Strong frame houses lifted off foundations and carried considerable distance to disintegrate; automobile-sized missiles fly through the air in excess of 100 yards; trees debarked; incredible phenomena will occur.

Source: The Enhanced Fujita Scale (National Weather Service). http://www.crh.noaa.gov/arx/efscale.php

Table 3–29 Significant Tornado Events from 1950 to 2012						
Event number	Date	Time	F/EF Scale	Injuries	Fatalities	$ Loss (Millions)
624	8/12/1957	13:30:00	0	0	0	0
249	6/11/1958	15:00:00	0	0	0	0
618	7/19/1996	14:30:00	0	0	0	0
1200	11/17/2010	0:35:00	1	3	0	0.25

Tornado season is generally noted to last from March through August — although tornadoes may occur at any time of the year — and more than 80 percent of tornado strikes happen between noon and midnight. Tornadoes are known to destroy almost everything in their path. Depending on the intensity and size of the tornado, damage may be as minor as a few broken tree limbs and downed power lines, or as devastating as the destruction of houses, businesses, and community vitality. Nationwide, tornadoes account for an average of 70 fatalities and 1,500 injuries each year. From events reported between 1950 and 2010, tornados in Baltimore produced a total of $203,617 in reported property damage, or $3,338 annually (Table 3–28 Tornado Hazard - Property Damage in Baltimore, below).

To date, the highest intensity tornado experienced in the Baltimore Region has been an F2. One such event on June 16, 1973 injured four people in the Towson area. In October 1990, another F2 tornado injured 59 Reisterstown residents. Less than twenty minutes later, this tornado was followed by a less powerful, F1 tornado. A more in-depth collection of significant tornado events in the Baltimore Region is listed in Table 3–29 Significant Tornado Events from 1950 to 2012.

Tornado over Inner Harbor, June 2013

Table 3–28 Tornado Hazard - Property Damage in Baltimore	
Property Damage (Total)	Property Damage (Annualized)
$ 203,617	$ 3,338

Source: Table 3-73, Maryland Emergency Management Agency, 2011: 192.

Derechos

Derechos are large thunderstorm clusters that produce widespread and long-lasting winds which can be extremely damaging. The impact of a derecho is similar to that of a hurricane making landfall, and can be many miles wide and several hundred miles long. An event may be classified as a derecho if the swath of storms is more than 240 miles long and wind speeds of over 58 mph are maintained for at least six hours throughout the entire span of the storm front.

Derechos occur most often in the Midwest and Great Lakes region during the summer months. In the Mid-Atlantic region, derechos are less common — occurring once every two to four years in Maryland. Consequently, residents have typically been less familiar with this type of storm designation. The term, however, was recently marked in the memories of many Baltimore residents following the devastation of a June 29, 2012 Mid-Atlantic and Midwest derecho. According to the National Weather Service, this storm, which was exceptionally severe in the Baltimore/Washington region, brought gusts of wind between 65 and 75 mph. As a result, numerous overhead electrical units suffered damage, two individuals were electrocuted by downed power lines, and more than one million customers across the region were left without power. In some areas, efforts to restore power persisted for more than a week. Additionally, these strong winds disrupted communication with vital emergency response facilities, interrupting 911 services in Northern Virginia. Maryland declared a state of emergency as the National Weather Service Forecast Office of Baltimore/Washington received over 300 early reports of severe damage, and continued gathering reports in the weeks that followed.[31] In Baltimore City, public sector costs of the June 29th storm exceeded $2.5 million. A list of additional derechos in Maryland is collected in Table 3–30 Noteworthy Derechos Impacting MD, above.

Table 3–30 Noteworthy Derechos Impacting MD

Date	Description
June 6, 1977	Southern-Mid-Atlantic Derecho
July 4-5, 1980	"The 'More Trees Down' Derecho"
November 20, 1989	"The Mid-Atlantic Low Dewpoint Derecho of November 1989"
April 9-10, 1991	"The West Virginia Derecho of 1991"
August 4, 2004	n/a
May 21, 2004	n/a
July 10-11, 2011	"The Cross Country Derecho of July 2011"
June 29-30, 2012	"The Ohio Valley / Mid-Atlantic Derecho of June 2012"

Source: http://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm

The Mid-Atlantic Derecho of 2012 as it approaches Baltimore's Inner Harbor *Source: Buddy Denham*

A number of other hazards may also be associated with derechos — including heat waves, tornados, and flash floods. As derechos occur in the summer months, they may indirectly lead to fatalities if power outages correspond with extreme heat waves. Indeed, this is a significant concern as derechos often appear on the fringe of heat waves due to favorable storm conditions created by extreme shifts in temperature. In the derecho of 2012, for example, Baltimore experienced a record setting heat wave, where temperatures measured at BWI Airport reached or exceed 90°F for 12 consecutive days.[32] This heat wave began on June 27—two days prior to the derecho event— and high temperatures endured for more than a week while hundreds of thousands of residents were deprived of power and/or air conditioning.

It should also be noted that the same conditions which foster the formation of a derecho are also favorable conditions for tornados. Furthermore, the immense downpour of precipitation associated with derechos and thunderstorms may lead to instances of flash floods.

The Mid-Atlantic Derecho of 2012 *Source: umd.edu*

2012 Derecho Impact on the City of Baltimore

Damage from the Mid-Atlantic Derecho was extensive. Many of the City's trees were uprooted or snapped causing widespread power outages. The storm ripped off sections of roofs and many cars were crushed by debris. In some areas, it took nearly 10 days to restore power.

Source: Tree Baltimore and Kim Harris

Source: http://www.lternet.edu/

Extreme Heat

An extreme heat condition is identified when prolonged temperatures are 10° or more above the average high temperature for a region. In Baltimore's past, between the 1950's and the 1970's, an average of 60 percent of summer days had met the maximum temperature extremes. In the 2000's, that percentage grew to approximately 75-90 percent of summer days reaching maximum temperature extremes. Studies predict that Baltimore may experience between 85-95 percent such days before the middle of the century, or between 90-95 percent by 2100.

These extreme heat predictions may be further evaluated by considering what temperature extremes are being met. Between 1981 and 2010, Baltimore experienced an average of 1.1 days a year with temperatures above 100°F. In 1930, Baltimore endured its longest stretch of 100 degree days, spanning a four-day period between July 19th and 22nd. A three-day stretch was experienced in 2011, between July 21st and 23rd.[33] Conservative projections for Baltimore City estimate that the number of days with temperatures above 100°F could increase to as many 1.6 days a by 2050, or 2 days a year by the end of the century. Similarly, in the Northeast region, low emissions scenario projections estimate a regional increase to as many as 9 days a year by the middle of the century.[34]

According to NOAA, Baltimore experienced an average of 31 days a year when temperatures met or exceeded 90°F in the years between 1981 and 2010. In 2012, the June 29th derecho occurred on the fringe of a major heat wave in Baltimore. For more than a week straight, temperatures soared above 90°F. In Baltimore, the number of days when temperatures reach or exceed 90°F are projected to increase to between 35 and 38 days by 2050, or to between 38 and 41 days a year by the end of the century. Similarly, according to the National Climate Assessment, regional climate model simulations suggest that Maryland could experience more than twice as many days per year over 95°F by mid-century — with an estimated 15 additional days above 95°F each year.[35] This is expected to severely impact vulnerable populations, infrastructure, agriculture and ecosystems. In the future, Baltimore expects that periods of extreme heat are likely to increase in frequency, duration, and intensity.

The summer season in Baltimore City is known to have frequent high temperatures accompanied by high humidity. On some summer days, urban air can reach temperatures up to 10°F warmer than surrounding suburban or rural areas — a phenomenon known as the "urban heat island effect." Densely developed, metropolitan areas tend to replace natural land cover with asphalt, sidewalks, buildings, and other hard infrastructure. As opposed to natural elements of an ecosystem, which can absorb the sun's heat and cool the surrounding air through evapotranspiration, these hard materials retain and radiate heat. The resulting warm urban temperatures can give rise to adverse public and environmental health problems, and can increase energy usage for summertime cooling.[36] The urban heat island effect is anticipated to become intensified as extreme heat events increase as a result of climate change.

The 2001 satellite images of Baltimore City (Figure 3–90 and 3-11) shown below illustrates how intensely developed land contributes to rising temperatures near the city center. The left image shows impervious surfaces in the Baltimore metropolitan area, where the darker red areas represent dense, highly developed land. When compared to the land surface temperature image on the right, these same areas correspond with the hottest surface temperatures. Cooler areas correspond with open spaces, and low density development. According to the NASA Goddard Space Flight Center, Baltimore's land surface temperature changes by as much as 10 degrees Celsius going out from the city center.[37] More densely developed areas typically contain more materials (asphalt for example) likely to absorb and retain heat than rural areas.

While air conditioning is far more common today than it was in the past, there are many Baltimore residents who live without this luxury, either because of the associated expense or a personal choice. Row home style housing, which is typical of Baltimore, can become extremely hot during 90+ degree days and nights. Older residents may recall traditions of sleeping out on rooftops or in City parks to find relief from the heat. Today, however, these options are seen by most residents as unsafe or undesirable.

Below: Side by side, these two images compare Baltimore City's developed land (left) with land surface temperature readings.

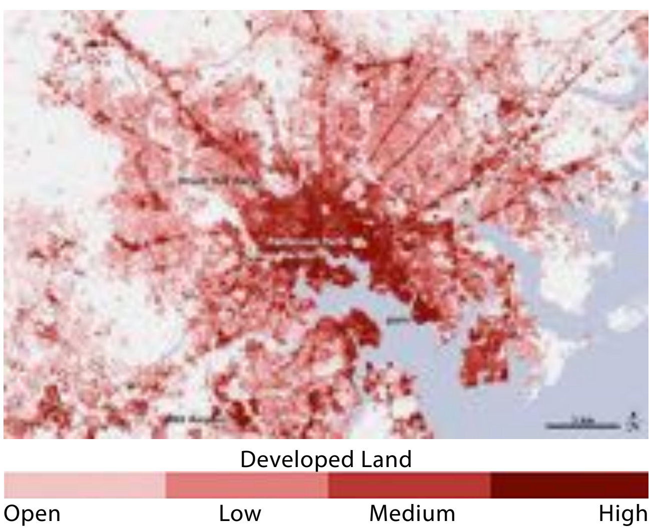


Figure 3–9 Developed Land in Baltimore City

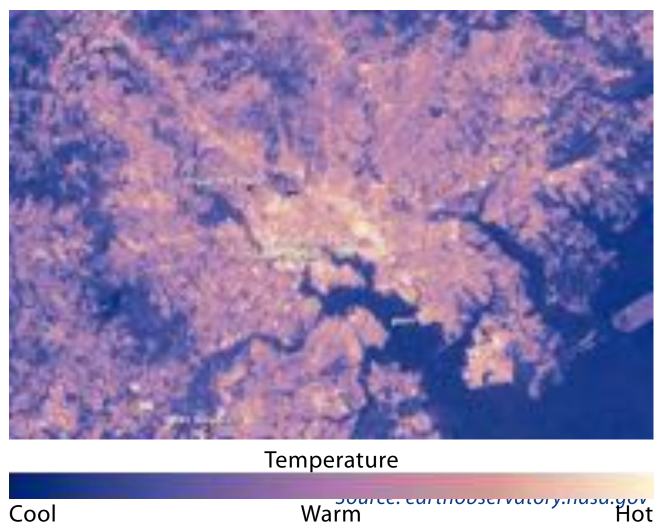


Figure 3–10 Surface Temperature in Baltimore City

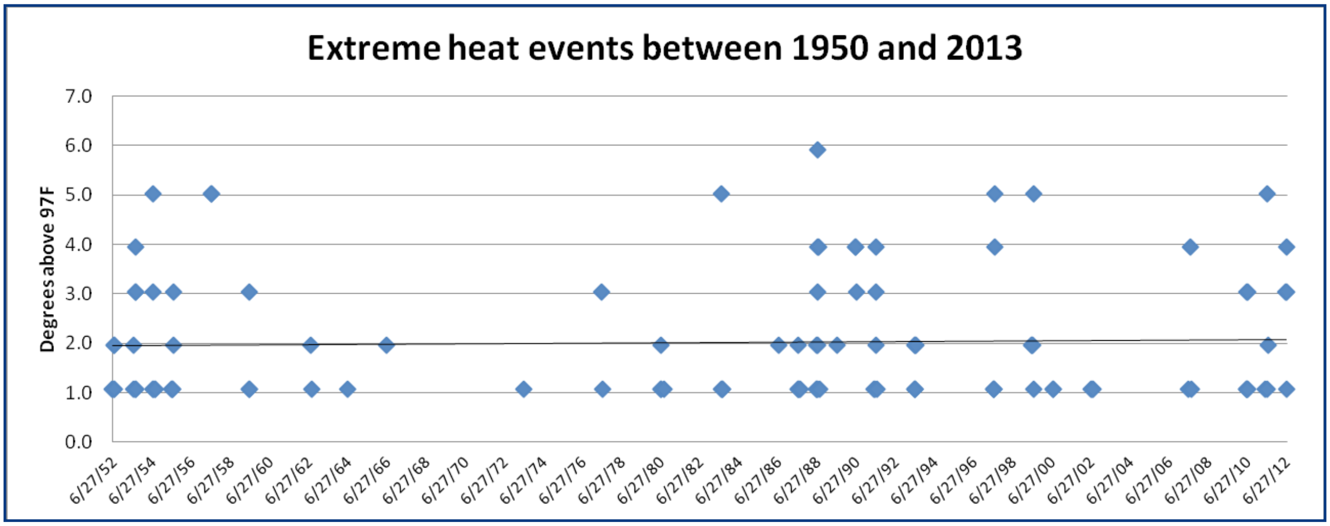
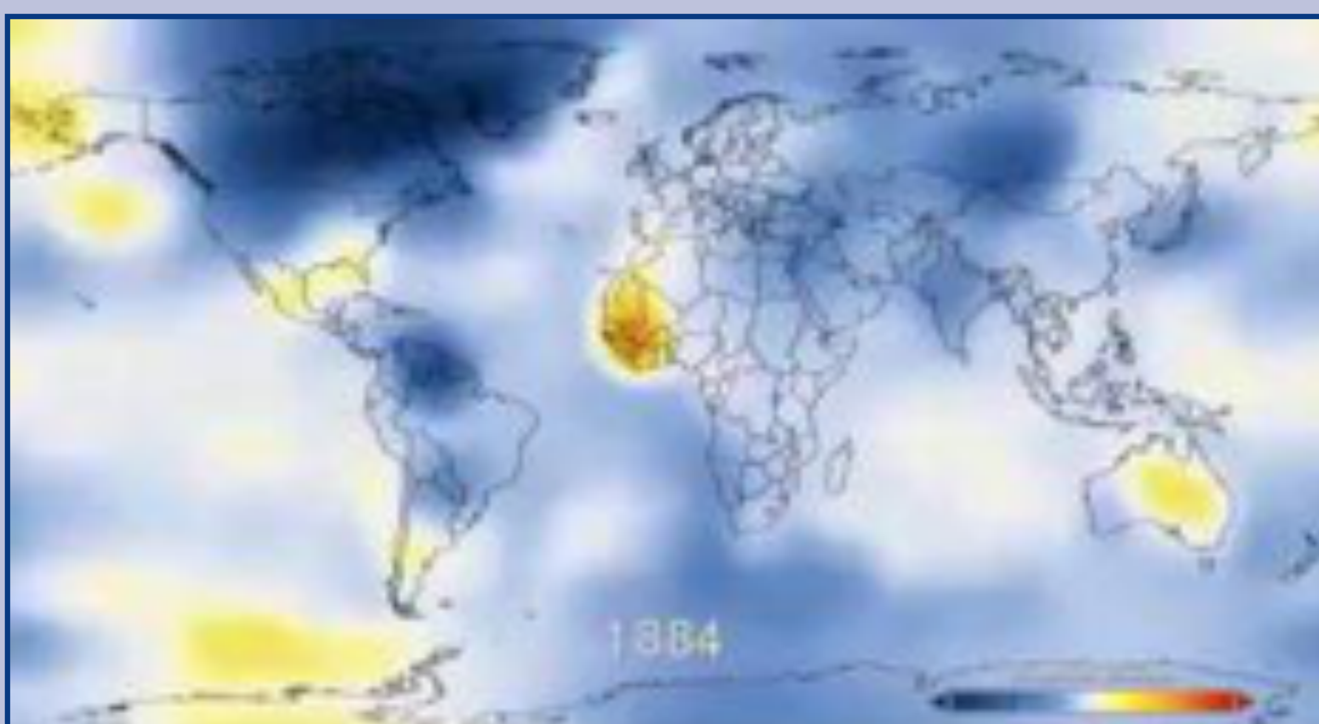


Figure 3–11 Extreme Heat Events in Baltimore Between 1950 and 2013

Over the past 50 years, average temperatures in the United States have increased more than 2°F. By 2100, Maryland's average winter temperature are projected to increase by 2-6°F and average summer temperatures are projected to increase by 3-9°F.[38] Greenhouse gas (GHG) emissions will impact future scenarios; as GHG emissions continue to rise, so will average temperatures. Increases in average temperatures will lead to longer consecutive periods of 90°-100°F temperatures. Figure 3–11, above, shows that the short period between 1960 and 1980 characterized by fewer high heat days was disrupted in the late 1980's onward by years with more frequent days reaching temperatures above 97°F.

A significant increase in the number of extreme heat days could place people at a greater risk of suffering from heat-related health conditions, including heat stress, heat exhaustion, or heat stroke. These medical problems are a particular threat to the elderly population, young children, or people with respiratory difficulties. For instance, in the heat wave following the June 29, 2012 derecho, a total of 8 heat-related fatalities were reported in Baltimore City.[39]

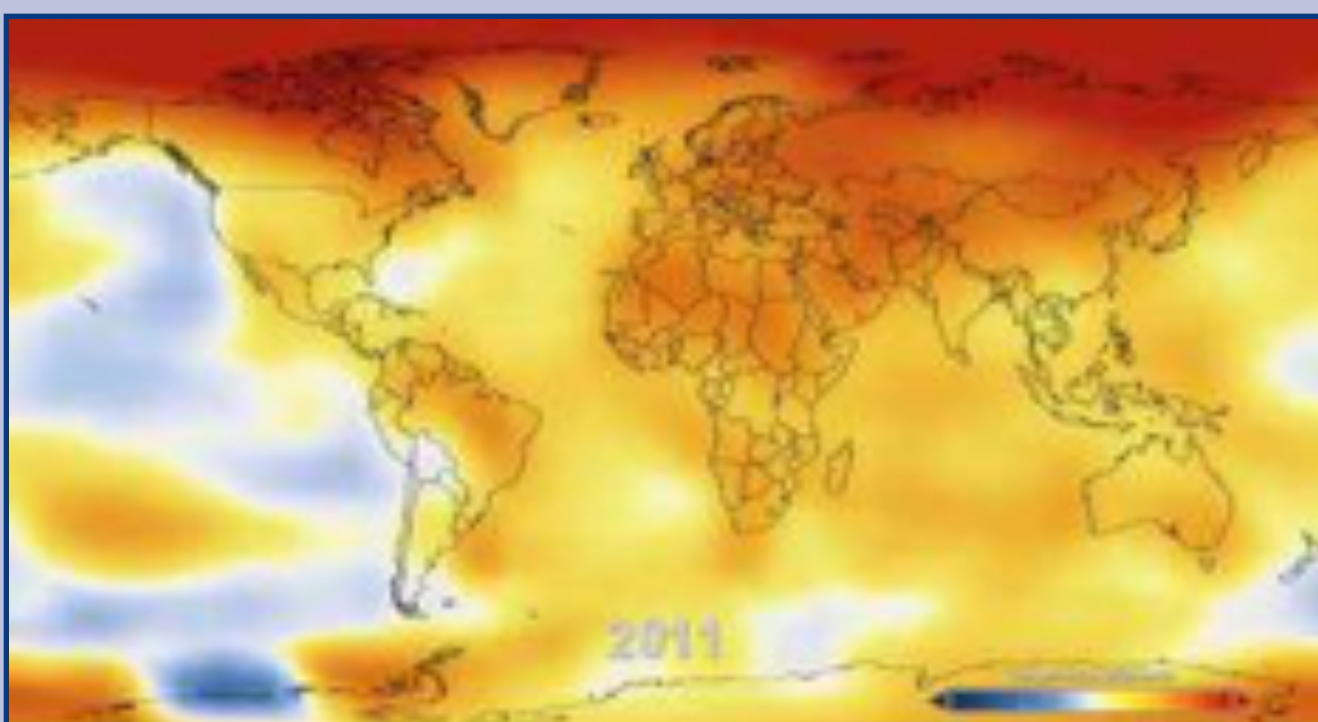


Average Global Temperature in 1884

Source: NASA

Figure 3–12 Heat Related Mortalities in Baltimore City

Heat Fatalities in Baltimore City (pre-2005 data is provided by CDC, but starting 1989, data is "suppressed" if less than 10 for privacy purposes. Data from 2005 onwards is from BCHD). Also presented is monthly heat mortality since 2005, with average monthly temperature.



Average Global Temperature in 2011 *Source: NASA*

Air Quality & Respiratory Illnesses

Health risks associated with heat — particularly risks that worsen symptoms triggered by respiratory diseases — are further provoked by diminished air quality. Trees and other vegetation cool the surrounding air and are shown to help to improve air quality. According to the American Lung Association, Baltimore City received a D Grade in the 2013 Air Quality Report Card.[40] The map right, Figure 3–1414, utilized air quality trends to grade air quality in Maryland. The Baltimore region, highlighted in red, received an 'F'.

Acting as filters, trees gather find particles from the air, and scientists have long considered the capacity of trees to affect air pollution. Researchers with the U.S. Forest Service, studying a number of cities including Baltimore, were recently able to quantify one health benefit of the urban tree canopy. Their study found that trees in Baltimore remove approximately 14 tons of pollution each year.[41] Tying these findings to public health, this service is equated with one less premature death, nearly 140 fewer asthma attacks, and avoiding an estimated 240 cases of labored breathing. Other highly populated cities with denser tree canopies have shown even greater influence. In New York City, for example, the study estimated that the tree canopy could be credited with preventing as many as 8 deaths.

Summertime heat increases energy usage which, in turn, produces emissions that boost the concentration of harmful pollutants in the air. Furthermore, higher temperatures accelerate the chemical reaction that produces ground-level ozone, or smog. By the middle of the century, Baltimore is expected to endure a 28 percent increase in the average number of days exceeding 8-hour ozone standards.[42] Coupled with the possibility of higher pollen generation from plants due to a changing climate, air quality conditions may become a more considerable threat. Air pollution triggers asthma attacks, exacerbates allergies, and can lead to long-term health problems such as heart disease or stroke. Currently, asthma is the number one chronic disease among this nation's youth, afflicting one out of every 10 schoolchildren. Higher cases of these heat and air-quality induced conditions can place a stress on medical facilities.

Baltimore City smog *Source: Baltimore Sun*

Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	[illegible]
Moderate	51 to 100	[illegible]
[illegible]	[illegible]	[illegible]
Unhealthy	151 to 200	[illegible]
Very Unhealthy	201 to 300	[illegible]
Hazardous	301 to 500	[illegible]

Figure 3–13 Air Quality Index *Source: LowerManhattan.info*

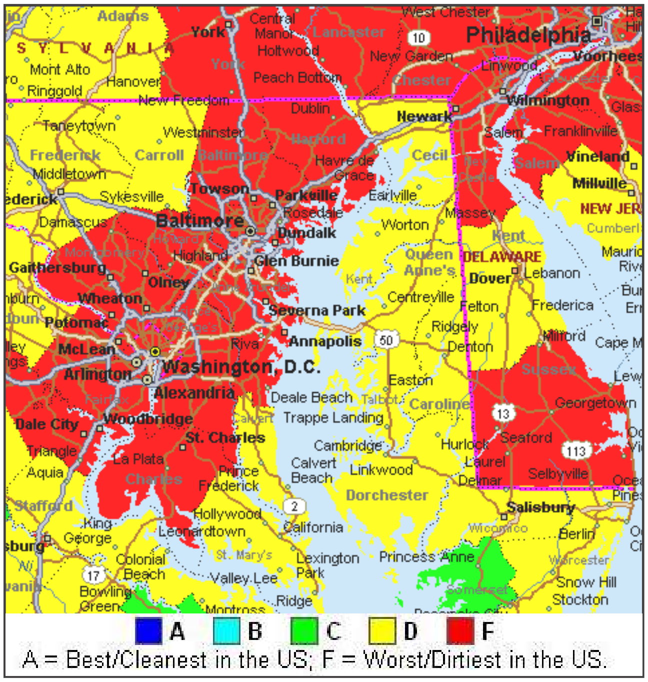


Figure 3–14 Maryland Air Quality

Source: http://creativemethods.com/airquality/maps/maryland.htm

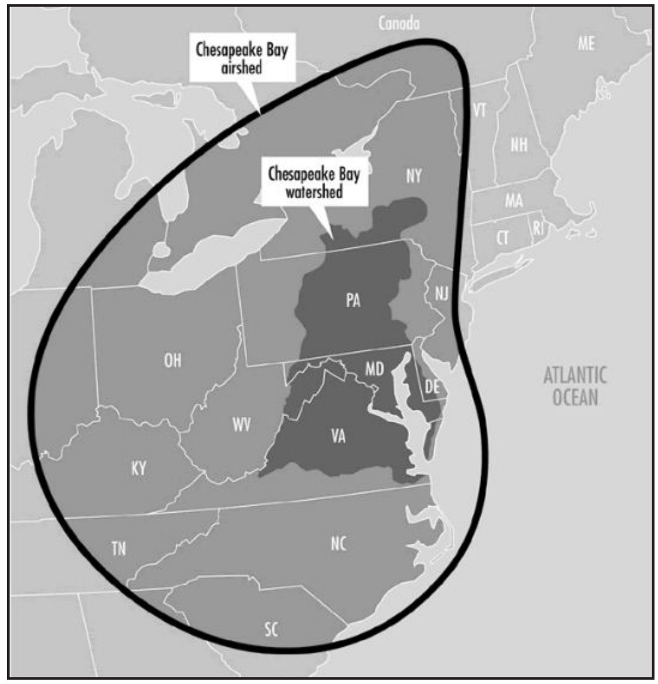


Figure 3–15 Chesapeake Bay Airshed

Source: Chesapeake Bay Foundation

Airsheds

The term **AIRSHED** refers to the specific air supply of a geographical region, and is used to measure the air composition (i.e. air pollutants) of that region. Airsheds are influenced by a number of factors, including urban development, hydrological and geographic features (i.e. water bodies and large land masses), and weather patterns.

An airshed is similar to the concept of a watershed; in fact, an airshed often shares a significant relationship with the watershed it encompasses. Air emissions sources in the Chesapeake Bay's airshed, for instance, contribute 75 percent of the nitrogen deposited from the air into the Bay and its watershed. For this reason, the Chesapeake Bay Program utilizes a three-model analysis — consisting of an airshed model, a watershed model and a model of the Chesapeake Bay estuary — to determine nutrient loads to the Chesapeake Bay under different scenarios for the purpose of closely examining the nutrient sources to a water body (for a more detailed review of this Cross-Media Model, refer to the Chesapeake Bay Program's website).

Just as a watershed may be impacted by pollutants released upstream, an airshed, too, may contain emissions released in distant regions. In the Chesapeake Bay region, the airshed covers an estimated 570,000 square mile area — seven times the size of the Chesapeake Bay Watershed — stretching from Canada down to South Carolina, and as far west as Ohio (Chesapeake Bay Glossary; EPA). Furthermore, according to the Chesapeake Bay Foundation (CBF), the extent of the airshed may vary depending on current weather conditions. The movement of air pollution has dangerous consequences:

> "Unfortunately, much of our air originates in areas of the Midwest dominated by polluted emissions from powerplants and motor vehicles. We generate plenty of air pollution from the same sources within our region, but the amount from outside sources essentially doubles it." (CBF, *The Chesapeake's Airshed*)

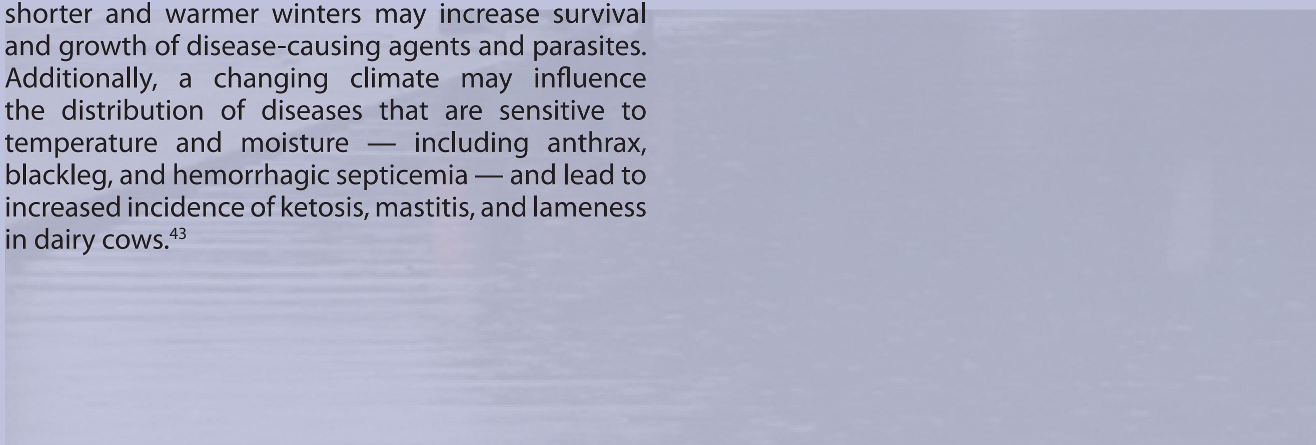
In addition to human health problems, this substantial air pollution load has severe environmental impacts through diminished air quality and pollution deposition in vital watershed ecosystems. Furthermore, as already noted, extreme temperatures that are intensified by the Urban Heat Island effect can also aggravate air quality. Higher temperatures increase pollution production, further reducing air and water quality.

Vector-Borne Diseases

Warmer, wetter conditions help insects and diseases flourish. In a changing climate, increases in average temperature, precipitation, and humidity will enable disease-carrying vectors and pathogens to infiltrate urban environments more easily. These conditions create favorable environments, for example, for breeding mosquitoes, which are known carriers of disease. Already, Baltimore has experienced a growing population of the tiger mosquito, originally native to Southeast Asia.

Aedes mosquito that transmits dengue fever *Source: endtheneglect.org*

According to the National Climate Assessment, shorter and warmer winters may increase survival and growth of disease-causing agents and parasites. Additionally, a changing climate may influence the distribution of diseases that are sensitive to temperature and moisture — including anthrax, blackleg, and hemorrhagic septicemia — and lead to increased incidence of ketosis, mastitis, and lameness in dairy cows.[43]



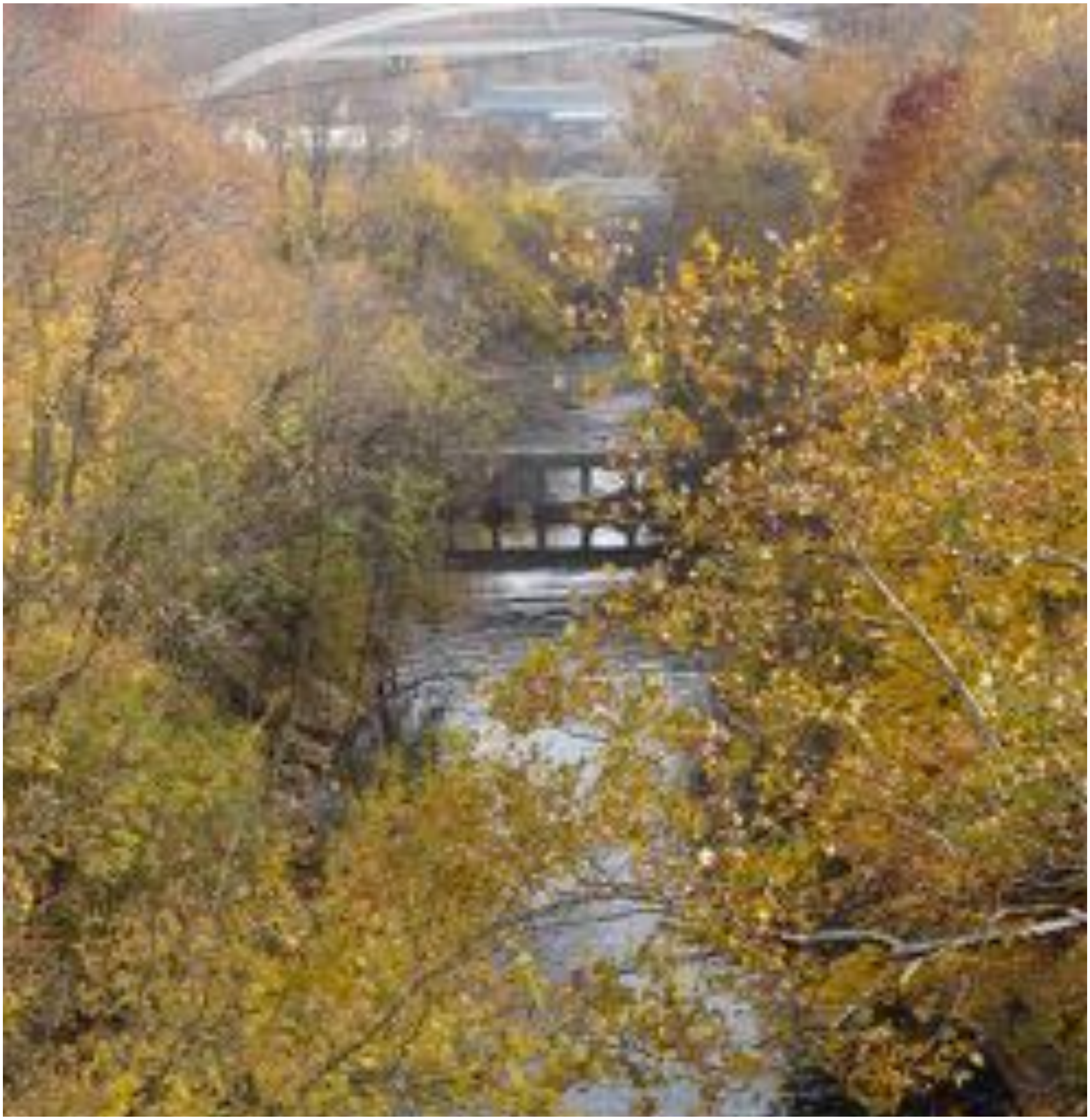
Standing water on Northern Parkway acts as a breeding ground for mosquitoes *Source: David Collins*

Extreme Heat Impacts on Infrastructure

Extreme heat in dense cities, as is typical of Baltimore City, can damage transportation and other infrastructure. Extreme heat damages transportation infrastructure, including streets, rail lines, and airport runways. Heat experiences may reduce the reliability and capacity of transportation systems. Extended periods with extreme heat can also tax the energy system, stressing or even damaging utility infrastructure.

Train tracks buckle during high heat event *Source: businessinsider.com*

Route 50 buckles in high heat *Source: State Highway Admin*



Jones Falls *Source: Blue Water Baltimore*

Trees and the Ecosystem

As mentioned above, the overall climate of the Baltimore region will soon be quite different from what we now recognize. With changing patterns, Baltimore's current climate zone is expected to be altered significantly. Summer months may soon feel more like the climate that is currently typical of southern states. As the overall climate begins to change, there will be a major shift in habitat conditions. We may, therefore, anticipate new challenges for native wildlife and vegetation.

As new species of insects, plants, and animals invade the Baltimore region, native species are challenged to compete for survival. However, at the same time, their native habitats grow more harsh and unfriendly. Changing precipitation patterns, for example, can dehydrate trees which may be simultaneously exposed to outbreaks of pests or diseases. Coping with intense struggles on two levels will place tremendous stress on a species.

Impacts on Water Sources

While drought is one threat to water supply (see Precipitation Variability Hazard Profile), extreme heat is another; and it is possible that Baltimore could experience both conditions at the same time, amplifying the impact. Extreme heat may actually increase the frequency and likelihood of drought events. In spite of projections of moderate increases in annual precipitation in Maryland, increases in temperatures in climate models lead to decreases in soil moisture throughout the year. In Maryland, the number of days above 90°F is projected to more than double under a lower greenhouse gas emissions scenario and roughly triple under a higher emissions scenario by the end of the century. Extended heat waves (temperatures above 90°F for at least three consecutive days) are expected to be much more frequent and longer lasting, particularly under higher emissions scenarios.

Maryland's diverse geology and water resources affect its vulnerability to drought. Ground water is the most commonly used source of water supply and is obtained from both confined and unconfined aquifers. Public water suppliers rely on surface waters for their water supply. About two-thirds of Maryland's citizens regularly consume water that originates from a surface water source. In general, counties that have invested in water supply and distribution infrastructure are generally less vulnerable to drought. However, communities relying on the Potomac and Susquehanna Rivers and their tributaries for water are more vulnerable during a drought than those using the Chesapeake Bay. This is due to the lack of recharge from surrounding watersheds (Figure 3–16) that flow into the rivers.

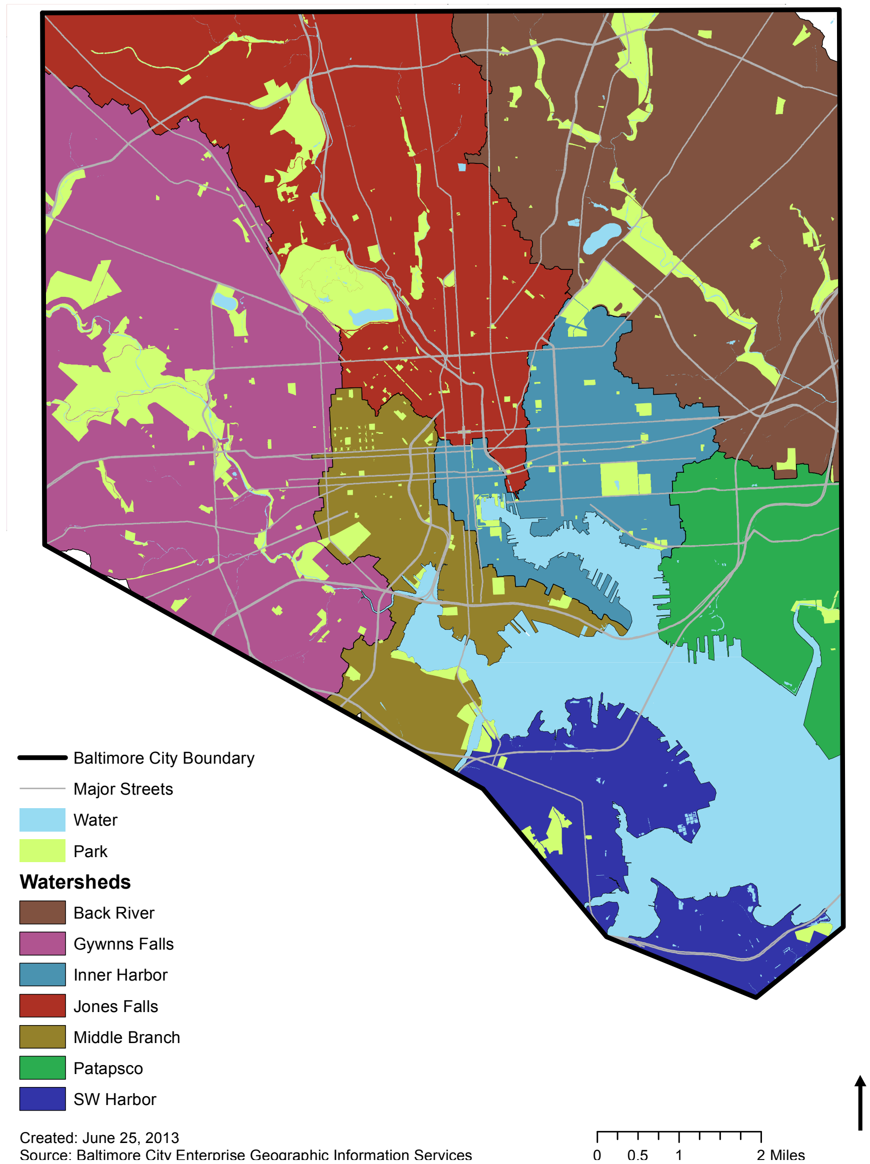


Figure 3–16 Baltimore City Watersheds

Baltimore City and Washington, D.C. rely on the Susquehanna and Potomac Rivers respectively. The Baltimore City water system was designed over 75 years ago to provide a year-round supply of water. If that supply is ever depleted, Baltimore can pump water into the City from the Susquehanna River through an existing 120" diameter water main. This back-up system, however, has never been needed. Whether or not this system is still functional is actually unknown. Meanwhile, Washington, D.C. has less than a week's supply of water if the Potomac River were to dry up.

Baltimore Hoop House *Source: Office of Sustainability*

Agriculture and Aquaculture

Agriculture is Maryland's largest industry, and drought is a significant, recurring problem. While many factors can influence agricultural productivity, declines in crop yields are most closely linked to insufficient precipitation (see Precipitation Variability). Depleted soil moisture can also have a direct impact on agricultural productivity and can continue to affect yields even after normal precipitation levels return. While agricultural production is not as significant in Baltimore, many City residents do rely on surrounding agricultural operations for their food supply.

More than just precipitation and soil moisture, however, crops may depend on other climatic conditions to thrive. The growing season, for instance, determines what crops can grow in the area during certain months. As the regional climate shifts, growing seasons for certain crops are extended. By the end of the century, the number of growing days in Maryland is expected to increase from 239 days a year to between 259-278 days a year.[44] To sustain familiar crops, farmers may begin to place an additional strain on water resources. While the growing season shifts, other crops may simply find it too warm to grow at all. For farmers with resources at hand, this may be seen as an opportunity. However, many farmers will find the adjustment challenging.[45]

Food security will be jeopardized in other ways. Animals will find it difficult to adapt to the changing climate and to respond to extreme temperature by altering their metabolic rates and behavior. According to the National Climate Assessment, increases in extreme heat events may place animals under conditions where their efficiency in meat, milk, or egg production is impacted.[46] Risk is intensified in animals used for meat production, as these animals are managed for a high rate of weight gain.

Baltimore is also susceptible to changing water conditions that will impact aquaculture operations. In addition to water quality concerns — levels of oxygen or the balance of nutrients — the City is also threatened by climate-related changes in aquatic environments. Marine environments are likely to change due to experienced increases in temperatures or from acidification. These conditions may force aquatic life to permanently migrate farther north, and can also increase instances of pathogens and disease, frequency and intensity of algal blooms, and the devastating effects of invasive species. Decreases in pH levels are caused by the buildup of carbon dioxide in the atmosphere. These changes make it more difficult for shellfish and similar creatures to develop their shells. Threat to aquaculture production is a global concern, and will therefore also have an effect on seafood goods which may be imported.

The aftermath of a 2011 Earthquake Event felt in Baltimore *Source: WBALTV*

Land

Earthquakes

An earthquake, also called a seismic event, is a trembling of the ground caused by the sudden movement of large sections — called tectonic plates — of the Earth's outermost crust. The edges of tectonic plates are marked by faults. Most earthquakes occur along fault lines when two or more plates slide past each other or collide against one another. As a result, the shifting masses send out shock waves that may be powerful enough to:

- Alter the surface of the Earth, thrusting up cliffs and opening great cracks in the ground and
- Cause great damage ... collapse of buildings and other man-made structures, broken power and gas lines (and the consequent fire), landslides, snow avalanches, tsunamis (giant sea waves) and volcanic eruptions.

Earthquakes are measured both in terms of their magnitude and their intensity. The effect of an earthquake on the Earth's surface is called the intensity. The intensity scale consists of a series of certain key responses such as people awakening, movement of furniture, damage to chimneys, and, finally, total destruction. Although numerous intensity scales have been developed over the last several hundred years to evaluate the effects of earthquakes, the U.S. currently utilizes the Modified Mercalli Intensity (MMI) Scale (Table 3–31). Developed in 1931 by a pair of American seismologists, the MMI scale distinguishes between 12 increasing levels of intensity — ranging from imperceptible shaking to catastrophic destruction — designated by Roman numerals. Because the MMI scale measures intensity based on the observed effects of an earthquake's impact on a particular area, it is often a better indication of severity to the nonscientist than is the measure of magnitude.

Earthquakes are low probability, high-consequence events. Although earthquakes may occur infrequently, they can have devastating impacts. Ground shaking can lead to the collapse of buildings and bridges; disrupt gas, life lines, electric, and phone service. Deaths, injuries, and extensive property damage are possible vulnerabilities from this hazard. Some secondary hazards caused by earthquakes may include fire, hazardous material release, landslides, flash flooding, avalanches, tsunamis, and dam failure. Moderate and even very large earthquakes are inevitable, although very infrequent, in areas of normally low seismic activity.

Table 3–31 The Modified Mercalli Intensity Scale of 1931 (abridged)

Intensity	Experience
I	Not felt except by very few people under especially favorable conditions.
II	Felt by a few people, especially those on upper floors of buildings. Suspended objects may swing.
III	Felt quite noticeably indoors. Many do not recognize it as an earthquake. Standing motorcars may rock slightly.
IV	Felt by many who are indoors; felt by a few outdoors. At night, some awakened. Dishes, windows and doors rattle.
V	Felt by nearly everyone; many awakened. Some dishes and windows broken; some cracked plaster; unstable objects overturned.
VI	Felt by everyone; many frightened and run outdoors. Some heavy furniture moved; some fallen plaster or damaged chimneys.
VII	Most people alarmed and run outside. Damage negligible in well-constructed buildings; considerable damage in poorly constructed buildings.
VIII	Damage slight in special designed structures; considerable in ordinary buildings; great in poorly built structures. Heavy furniture overturned. Chimneys, monuments, etc. may topple.
IX	Damage considerable in specially designed structures. Buildings shift from foundations and collapse. Ground cracked. Underground pipes broken.
X	Some well-built wooden structures destroyed. Most masonry structures destroyed. Ground badly cracked. Landslides on steep slopes.
XI	Few, if any, masonry structures remain standing. Railroad rails bent; bridges destroyed. Broad fissure in ground.
XII	Virtually total destruction. Waves seen on ground; objects thrown into the air.

Earthquake Fact Sheet, MGS, www.mgs.md.gov/esic/brochures/earthquake.html,

Table 3–32 Relationships among earthquake magnitude, intensity, worldwide occurrence, and area affected

General Description	Richter Magnitude	MMI	Expected Annual Incidence	Distance Felt (miles)
Microearthquake	below 2.0	--	600,000	--
Perceptible	2.0-2.9	I--II	300,000	--
Felt generally	3.0-3.9	II-III	49,000	15
Minor	4.0-4.9	IV-V	6,000	30
Moderate	5.0-5.9	VI-VII	1,000	70
Large (Strong)	6.0-6.9	VII-VIII	120	125
Major (Severe)	7.0-7.9	IX-X	18	250
Great	8.0-8.9	XI-XII	1.1	450

MGS, Earthquake Fact Sheet, www.mgs.md.gov/esic/brochures/earthquake.html

Figure 3–17 Peak Ground Acceleration Source: USGS; http://earthquake.usgs.gov/hazards/products/

Figure 3–18 Earthquake Events Originating Around Baltimore City Source: http://www.ncedc.org/acknowledge.html

Table 3–33 Earthquake Events Within 200 Miles of Baltimore City

Date	Location	Magnitude
8/23/2011	Louisa County, Virginia (37.94N, 7793W)	5.8
7/16/2010	Potomac Region (39.17, -77.25)	3.4
9/29/2009	Bel Air, Maryland (39.607, -76.342)	1.6
7/1/2009	SW New Jersey (39.64, -75.48)	2.8
12/27/2008	Lancaster, Pennsylvania	3.4
2/23/2005	SE Baltimore (39.26, -76.58)	2
12/9/2003	Virginia (37.599N, 77.932W)	4.5
8/26/2003	New Jersey (40.61N, 75.11W)	3.8
3/22/2002	Columbia, Maryland (38.19, -76.84)	1.0 to 2.0
12/18/2001	Columbia, Maryland (38.19, -76.84)	1.5 to 2.0
9/25/1998	Pennsylvania (41.49N, 80.38W)	4.5
12/22/1996	Columbia, Maryland (39.19, -76.87)	2.0, 2.3
12/16/1996	Ellicott City, Maryland (39.25, -76.77)	about 1.0
12/14/1996	Columbia, Maryland (39.19, -76.87)	<1.5
12/6/1996	Columbia, Maryland (39.19, -76.87)	<1.5
10/17/1996	Rising Sun, Maryland (39.7, -76.60)	2.2, 2.3
8/2/1996	Perryville, Maryland (39.57, -76.08)	22
10/28/1994	Glen Burnie, Maryland (39.1, -76.60)	2.7
1/16/1994	Pennsylvania	4
1/16/1994	Pennsylvania	4.6
11/27/1993	Columbia, Maryland (39.19, -76.87)	about 1.5
11/27/1993	Columbia, Maryland (39.19, -76.87)	<1.5
11/17/1993	Columbia, Maryland (39.19, -76.87)	1.7
10/28/1993	Ellicott City, Maryland (39.25, -76.77)	1.8
10/28/1993	Ellicott City, Maryland (39.25, -76.77)	2.1
7/12/1993	Columbia, Maryland (39.19, -76.87)	2.1
7/9/1993	Columbia, Maryland (39.19, -76.87)	1.9
4/8/1993	Columbia, Maryland (39.19, -76.87)	1.0 to 1.5
4/4/1993	Columbia, Maryland (39.19, -76.87)	1.5
4/4/1993	Columbia, Maryland (39.19, -76.87)	1.5
3/26/1993	Ellicott City, Maryland (39.28, -76.82)	<1.5
3/22/1993	Columbia, Maryland (39.19, -76.86)	about 0.0
3/21/1993	Aberdeen, Maryland (39.47, -76.30)	1.5
3/19/1993	Columbia, Maryland (39.19, -76.87)	<1.0
3/19/1993	Columbia, Maryland (39.19, -76.87)	1
3/17/1993	Columbia, Maryland (39.19, -76.87)	<= 1.0
3/16/1993	Columbia, Maryland (39.19, -76.87)	1.8
3/16/1993	Columbia, Maryland (39.19, -76.87)	1.8
3/15/1993	Columbia, Maryland (39.19, -76.87)	2.7
3/12/1993	Columbia, Maryland (39.19, -76.87)	2
3/10/1993	Columbia, Maryland (39.19, -76.87)	2.5
9/28/1991	Granite, Maryland (39.35, -76.83	2.4
4/4/1990	Granite, Maryland (39.35, -76.78)	1.7
1/13/1990	Randallstown, Maryland (39.36, -76.78)	2.6
5/23/1986	Accoceek (38.69, -77.04)	2.5
4/23/1984	Lancaster County, Pennsylvania	4.4
4/26/1978	Hancock (39.7, -78.24)	3.1
9/7/1962	Hancock (39.7, -78.20)	3.3

The Table (Table 3–33) and Map (Figure 3–18) display earthquake events within 200 miles of Baltimore City between 1950 and 2012. While no earthquake epicenters have been located within the City of Baltimore, strong earthquakes are capable of being felt for hundreds of miles. In 1897, the Giles County Virginia Earthquake measured 2.0 MMI in Baltimore. The strongest earthquake felt in the Baltimore region, however, was another Virginia earthquake that measured an intensity of 5.8, originating in Louisa County on August 23, 2011. This event caused considerable damage in Baltimore; a number of buildings were damaged, including the historic and celebrated Baltimore Basilica, which reported between $3-5 million in damages.

Compared to other parts of the United States, the Baltimore region has relatively low probability of experiencing strong earthquakes. Figure 3–17 shows the expected maximum horizontal ground acceleration (PGA) — or ground shaking — as a percent of gravity (%g). The Baltimore region has an expected peak acceleration of 8%g. At this level, as noted in Table X, any potential damage is expected to be very light.[47]

Landslides and land slumping may contribute to, or heighten, the probability of earthquake events in Baltimore. Landslides often occur along steep slopes, karst terrain (see below), or otherwise unstable land. Slopes greater than 15 percent often become unstable due to one, or a combination of, conditions including loose soil or rock, lack of vegetation, insufficient moisture, or instability during or after an earthquake. The Maryland Geological Survey (MGS) does not consider Baltimore to have a significant risk of landslide due to the lack of mountainous areas. While there are indeed some steep slopes, particularly near streams, these slopes are usually vegetated and stable, and are therefore unlikely to instigate minor earthquakes.

The Maryland Geological Survey does caution, however, that land slumping could become a significant hazard in the event of a major earthquake. Downtown Baltimore has been developed upon a considerable amount of artificial fill that extended into harbor waters. Deposited into the water as a means to dispose of debris after the Great Fire of 1904, the fill provided reclaimed land for the growing city. Were a severe earthquake to occur in or near Baltimore, scientists at MGS predict that many structures located atop the filled land would likely suffer significant damage.

West Baltimore Street

Source: thesinkhole.org

Risks of subsidence when combined with coastal hazards *Source: University of Maryland Center for Environmental Science*

Subsidence

Land subsidence is the gradual settling or sinking of the Earth's surface. Subsidence may be gradual or sudden and can range in extent—from broad, regional reductions in elevation to localized areas of collapses. It is often caused, principally, by aquifer system compaction, drainage of organic soils, underground mining, hydro-compaction, natural compaction, sinkholes, and thawing permafrost. Subsidence is a global problem; in the United States, more than 17,000 square miles in 45 states — an area roughly the size of New Hampshire and Vermont combined — have been directly affected by subsidence.

Regional subsidence is believed to be the result of post-glacial rebound following the last glacial maximum. The mass of the ice sheet had displaced land, pushing the surrounding land upward at the ice sheet's coverage (Chesapeake Bay region in Maryland). Ever since the ice sheets retreated, the elevated area has been subsiding. At the regional level, Maryland has been subsiding at a rate of approximately 1.5 mm/yr.[48] Recent climate assessments have reported Baltimore's rate of land subsidence to have been roughly half a foot in the last century.[49] When coupled with rising waters, local land subsidence can exacerbate relative sea level rise.

A Sinkhole in Baltimore's Canton Neighborhood, O'Donnell Street, June, 2013 *Source: WBALTV*

Urban Karst/Sinkholes

The term "karst" refers to land that is characterized by various subterranean features—including sinkholes, caves/caverns, underground streams, and other features that are formed by the dissolution of calcium and magnesium oxides in certain rocks. Karsts may produce surface and subsurface conditions that give rise to a number of problems. According to a report published by the Western Maryland Resource Conservation and Development Council, Karst regions are prone to unpredictable or easily contaminated groundwater supplies.[50] Additionally, karst lands are susceptible to subsidence and other changes in land, such as sinkholes which present a physical hazard. Karst formations develop in specific ways that are influenced by unique local conditions. These geological conditions are not naturally present in Baltimore, and so the City is not significantly impacted by karst formations. In fact, to date, there have been no Federal Declared Disasters or NCDC recorded events for karst-related hazards in all of Maryland.[51]

In addition to natural processes, however, sinkholes can be induced through human actions. Human-induced sinkholes can be triggered by simple alteration in the local hydrology. Inadequate drainage along highways and increased runoff from pavement can also be sources of sinkhole development. In Baltimore, infrastructure-related sinkholes have been the primary concern.

Maryland is affected by a broad, regional subsidence phenomenon and more localized land collapsing due to sinkhole formation. Sinkholes have the potential to cause damage to infrastructure and buildings and may result in injuries or even fatalities. When coupled with heavy rainfall, risks associated with sinkholes may increase. In August of 2012, following heavy rains, a sinkhole opened on Baltimore's East Monument Street above a 120-year-old drainage culvert. When another storm released an estimated one to three inches of rain on top of the repair effort, emergency workers were forced to once again evacuate the site.

The impact was extensive; not only was the roadway closed due to repair and reconstruction, but the drainage pipe beneath it, "the main artery draining storm water to the Inner Harbor for hundreds of acres," was also out of commission — unable to accommodate those heavy rains, contributing to local flooding and leading to additional sinkhole damage.[52] It took five months for crews to complete restoration — a project that cost the City $7 million (not including the economic impact on four blocks of affected area businesses, which was severe).[53] Furthermore, additional funds would still be needed to fully repair the three water utility lines below the roadway.

Sinkhole on E. Baltimore Street, May 2011 *Source: pattersonparkpatter*

Sinkholes appear to be happening more frequently. An article from December 2012 noted that sinkholes had been occurring in large numbers across the country, suggesting that frequent and large sinkholes may be quickly becoming the "new normal." The article noted that, in Baltimore specifically, more than four sinkholes had recently developed in three weeks that December. In fact, the article states that "as [Baltimore] crews worked on one sinkhole, another opened up about 125 ft. west of the original sinkhole widening rapidly within 15 minutes" noting also that two Fells Point homes were sinking during the same time period.[54] While it would appear that sinkholes are becoming more of a threat in Baltimore, it remains difficult to identify key sensitivities.

Sinkhole on W. Baltimore Street, August 2011 *Source: thesinkhole.org*

Table 3–34 Major Baltimore Sinkholes in the Past Decade

Race and West Street	2008
2238 East Monument Street	2009
2100 S. Clinton Street	2009
600 Cathedral Street	2011
I-83 & 29TH Street	2012
2300 block of East Monument Street	2012
W 37th and Keswick	2013
721 Gorsuch Avenue	2013

Source: Baltimore City Department of Public Works