DELAWARE
Climate Change Impact Assessment

PREPARED BY

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Delaware Department of Natural Resources and Environmental Control

Section 3: Delaware's Resources

Chapter 5 – Public Health Summary

Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century (**Figure 5.1**).

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

- Heat waves, or consecutive days with sustained high temperatures, are expected to increase. Heat wave events in which temperatures are

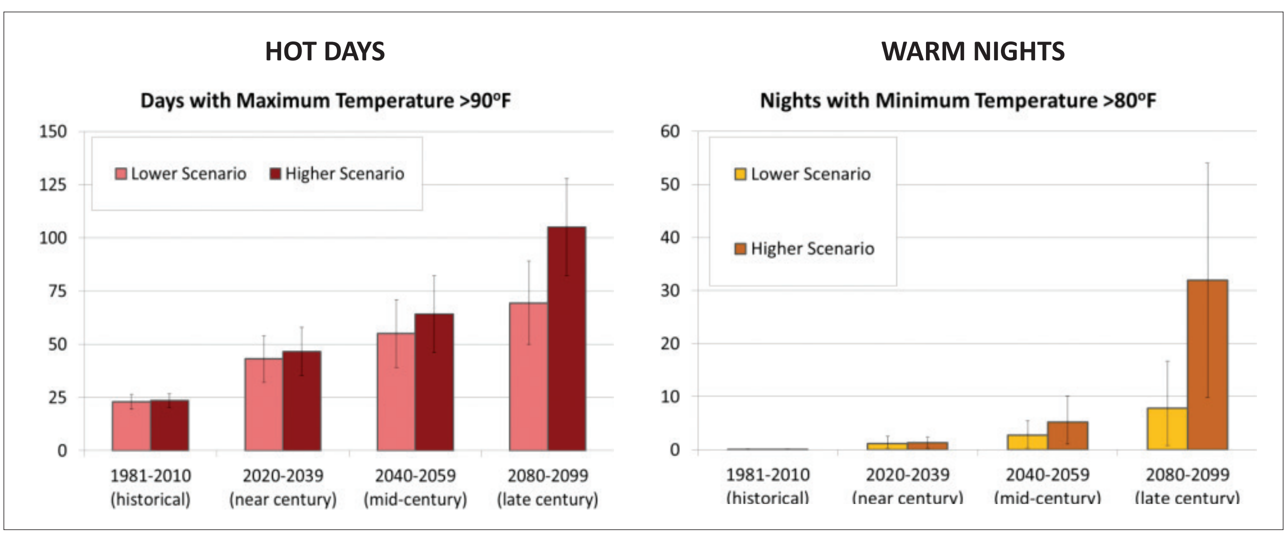

Figure 5.1 Increasing daytime and nighttime temperatures. Source: Hayhoe et al. (2013).

over 95°F are projected to average 12 days (lower emission scenario) to 25 days (higher emission scenario). Hundred-degree (100°F) heat wave events over the next century could average around 4 days under a lower scenario and 13 days under a higher scenario.

Precipitation Changes

- Average precipitation is projected to increase by an estimated 10 percent by end of century, consistent with projected increases in mid-latitude precipitation in general.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

Potential Impacts to Public Health

- Delawareans' exposure to increased temperatures is projected to increase over the next century, especially in the summer months. Human health is directly affected by high heat. Delaware is likely to confront an increase in heat-related mortality and morbidity.

- Delawareans at risk to heat: Communities and individuals who are economically disadvantaged and/or have underlying illnesses may have increased impacts related to heat stress. Urban communities – specifically those without access to cooling – may suffer from increased impacts due to heat island effects.

- Delaware's air quality may continue to degrade as conditions for ground-level ozone increase (increased temperatures and heat waves). It is likely that without additional regulations or policies to control the pollutants that cause ground-level ozone, concentrations will increase and affect the health of people living in Delaware.

- Increasing precipitation and temperatures may lead to conditions that are ideal for increased exposure to allergens as well as pathogenic diseases. Relationships among the environment, organisms, and diseases are complex; however, increases in ideal breeding conditions (temperature and precipitation) or habitats for harmful organisms may increase human exposure.

- Risk factors play a strong role in community health as well as in individual health.

Chapter 5 – Public Health

Chapter Contents

5.1. Overview of Climate Change and Public Health

Human health is inextricably linked to the surrounding environment. The interactions between humans and their environment drive the spread of diseases and contribute to illness and even death. This section examines the role that climate plays with human health; how changing climatic conditions affect human health; those factors that contribute to increases in illness and mortality; and the public health vulnerabilities that the state of Delaware may face with a changing climate. The public health impacts of climate change transcend geographic borders—many of the issues discussed in this section are not unique to Delaware and continue to be of regional and national significance.

This chapter examines a variety of climatic impacts on human health, including temperatures, air quality, and disease. Direct impacts on human health are those impacts that are directly attributed to the change in the surrounding environment, primarily the human response to temperature. Indirect impacts are more nuanced and/or have an intermediate factor that influences human health. The indirect impacts on human health are those changes in the environment that shift how diseases spread, how organisms grow and proliferate, and how environmental factors can aggravate underlying health conditions. Extreme weather events such as hurricanes, nor'easters, coastal flooding, and other natural hazards directly affect public health, safety, and security. Public safety is considered in the infrastructure chapter (9).

A critical component of understanding human health is a population's or community's risk factors. Risk factors include but are not limited to age, socioeconomic status, access to medical care/facilities, and the surrounding built environment. These risk factors cannot be ignored when understanding a community's vulnerabilities to climate change and preparing for public health interventions.

5.2. Direct Impacts on Public Health Related to Climate Change

5.2.1. Temperature

Temperature, especially temperature extremes have direct and measurable impacts on the human body, and all people, regardless of age, socioeconomic status, and race are susceptible. Some of the visible impacts related to temperature include heat rash and frostbite; other impacts include exacerbation of underlying health problems such as cardiopulmonary conditions. It is critical to note that although temperature has direct effects on human health, some effects may be delayed and difficult to attribute to one temperature event. This section will discuss both high- and low-temperature impacts on human health and the changes associated with climate change.

Every year, attention is given to extreme heat and cold events, including in the state of Delaware. In general, Delaware's climate is considered temperate, characterized by warm to hot summers and cold winters. Delaware has two temperature zones: the north and the south. The northern climate zone includes New Castle County, where the average temperature is 54.0°F. Kent and Sussex Counties make up the southern climate zone, where the average yearly temperature is 58.1°F. Though Delaware is considered a temperate climate, extremes in temperature can affect human health throughout the state. It is well documented that illness and death increase as temperatures deviate from the region's average temperature range, even if the deviation is not considered extreme.

As temperatures deviate from typical ranges, illness and mortality become more prevalent. The mechanisms that account for the body's reaction to heat and cold are the same: the body must work harder to maintain a steady core temperature.[2] Once the body cannot regulate the core temperature, illness and mortality begin to occur. Not all responses to temperature are straightforward. As mentioned above, some of the direct impacts of temperature are easily understood and attributed to exposure to extreme temperatures, while other impacts may be more nuanced. These indirect impacts include the exacerbation of underlying health conditions, which may delay onset of illness and/or even death. Studies have found that the onset of temperature-related mortality varies between hot and cold events. Mortality almost immediately peaks (2 to 5 days) following a high heat event, while mortality following a cold temperature event can be delayed up to 30 days.[3] Recognizing this deviation in mortality is important for responding to and preparing for extreme temperature events in those populations most at risk.

Extreme Heat

Heat is the leading cause of weather-related death in the United States.[4] The Centers for Disease Control and Prevention (CDC) defines a heat wave as, "A period of abnormally and uncomfortably hot and unusually humid weather. Typically a heat wave lasts two or more days."[5] There are plenty of examples of the impacts of heat waves across the nation, including the 2006 California heat wave that claimed the lives of 400 people[6] and one of the most notable U.S. heat waves, which occurred in Chicago in 1995 and resulted in at least 700 deaths.[7] These events, along with others around the globe, continue to gain the attention of the public and government officials.

Prolonged exposure to heat, especially high heat days combined with high humidity, can cause death by overwhelming the body's cooling systems, leading to cardiovascular stress and failure. Direct impacts of heat include heat rash, heat cramps, heat exhaustion, and heat stroke. Heat stroke is considered the most serious heat-related illness; it occurs when the body can no longer maintain its core temperature. At that point body temperature may rise to 106°F or more in less than 15 minutes, causing death or permanent disability.[8] Another bodily response to heat is heavy perspiration. Loss of fluids further stresses the body's responses to heat and can limit the ability of the body's circulatory system. Heat rash, cramps, exhaustion, stroke, and dehydration account for a portion of heat-related mortality. Aggravation of chronic or underlying illnesses can also cause the failure of the heart, kidneys, lungs, and other internal organs as the body works harder to cool the core.[9]

Urban heat island impacts also play a role in public health. Urban areas typically have large amounts of asphalt, concrete, and other surfaces that absorb and retain heat, leading to higher temperatures compared to rural areas. In Delaware, the northern, more urbanized portion of the state can have temperatures higher than the southern region of the state. The U.S. Environmental Protection Agency (US EPA) states that in cities with one million or more people, annual average temperatures can be 1.8˚F to 5.4˚F higher than surrounding rural areas. Exposed urban surfaces (e.g., roofs, asphalt, etc.) can be heated 50 to 90˚F warmer than the surrounding air temperature. Even after the sun sets, the urban areas can be warmer than surrounding areas. As buildings, asphalt, and concrete cool in the evening, they slowly release the heat that was absorbed during the day, warming the night air. The urban heat island effect can exacerbate heat-related illness and mortality in urban areas.[10] Research has found that urban populations can be at a higher risk for heat-related illness due to the heat island effect,[11] especially people who do not have access to air conditioning or who have limited social interactions (isolation).

The CDC estimates that annual temperature-related mortality in the United States could increase from approximately 700 deaths today to as many as 3,000 to 3,500 by the end of the century.[12] Projections indicate that annual average and summertime temperatures in the Mid-Atlantic region, including Delaware, will be warmer. Average temperature projections for Delaware in the near term (2020-2039) are for increases of 1.5 to 2.5°F. By mid-century (2040-2059), the lower emission scenario projects changes ranging from 2.5 to 4°F and the higher emission scenario projects that changes could be as high as 4.5°F. Extreme high temperatures are also expected to increase. Projections show that very warm days (temperatures over 95°F) are likely to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

Heat waves[a] are also expected to increase (**Figure 5.2**). Historically, there are on average around 2 consecutive days with temperatures over 95°F per year, and rarely days over 100°F (no more than one day per year). By late-century, the longest period of time over 95°F could average around 12 days per year under the lower emission scenario and up to 25 days per year under the higher emission scenario. Hundred-degree (100°F) heat wave events over the next century could average around 4 days (lower scenario) to 13 days (higher scenario).

[a] Dr. Katharine Hayhoe defines heat waves thus: "An extreme heat wave, based on Kunkel et al. (1998), is at least 4 consecutive days where average (day plus nighttime temperature) exceeds the historical 1-in-10-year event. In other words, such heat waves are calculated based on the historical record of the strongest heat wave per decade."

Extreme Cold

Exposure to cold can cause not only direct impacts such as hypothermia and frostbite, but also illness or mortality from respiratory infections such as influenza and pneumonia. Research continues to better explain how the spread of influenza and other respiratory diseases is affected by temperature changes.[13] There is a general correlation between annual average warming related to climate change and decreased mortality related to cold weather extremes. Delaware temperature projections estimate that the number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039 to only 3 to 4 days per year by 2080-2099.

5.3. Indirect Impacts on Public Health Related to Climate Change

5.3.1. Air Quality

Air quality is a serious health concern for Delaware's citizens. Historical levels of ozone and particulate matter have continually exceeded national standards under the Federal Clean Air Act, which is commonly referred to as nonattainment. In recent years, however, ozone and particulate matter levels are improving throughout the state.[14] Poor air quality is known to be harmful to human health through impacts on respiratory and cardiovascular systems. Air pollution in the

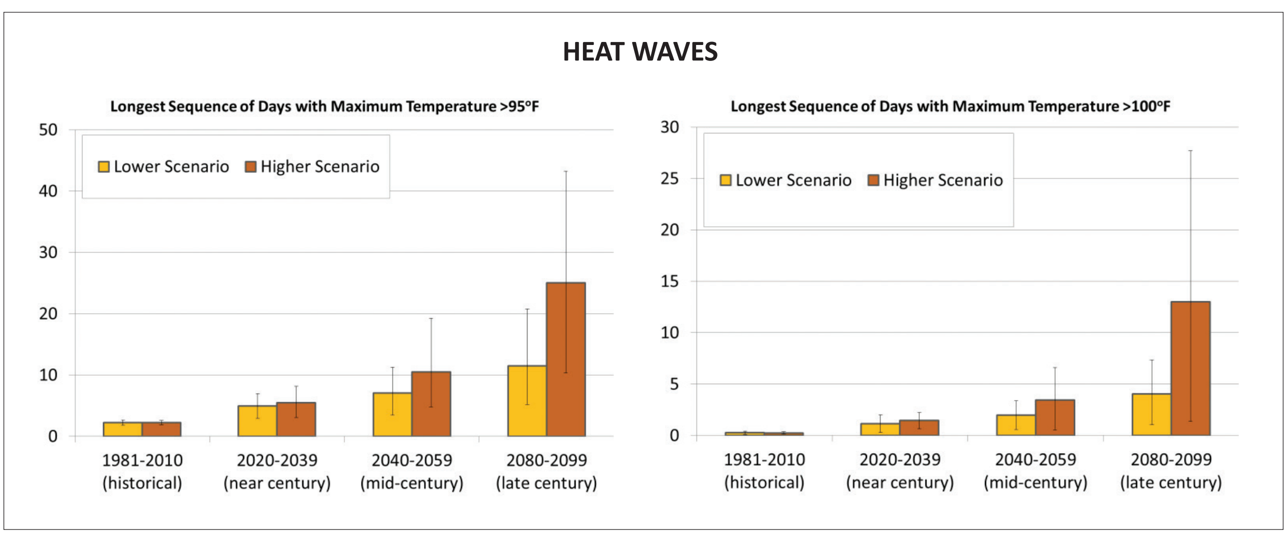

Figure 5.2 Consecutive days of extreme high temperatures. Differences between the high scenario and low scenario are greater by mid-century and end-of-century. Source: Hayhoe et al. (2013).

form of ozone and particulate matter is well known to irritate the lungs and airways as well as the cardiovascular system.[15] In addition, pollen and mold can cause allergic reactions in populations that have increased sensitivity.

Asthma is an issue in Delaware. A 2005 study found that almost 72,000 adults and 23,000 children in Delaware reported suffering from asthma at some point in their life. The yearly costs associated with asthma in Delaware were estimated to be $25 to 30 million. Although asthma can be triggered by a variety of factors, air pollution, poor air quality, and mold and pollen are well known to exacerbate breathing issues in asthmatic individuals.[16]

Ozone and Particulate Matter

Delaware is one of the most affected regions for ozone and particulate matter pollution in the United States. Trends indicate that although levels of both pollutants are improving in Delaware, there are still days every year when acceptable levels are exceeded. Specifically, the US EPA considers New Castle County as a nonattainment county for both ozone and particulate matter, and Sussex County is in nonattainment for ozone.

Delaware has made significant strides to improve air quality in the state. Since 1990, aggressive policies and regulations have targeted the precursor chemicals needed for ozone production as well as the sources of particulate matter.[17] This subsection examines ozone and particulate matter pollution and possible changes related to climate change.

Ozone

Ozone is a respiratory irritant that even at low concentrations can cause coughing, shortness of breath, and chest discomfort, and can be a trigger for asthma attacks. Humans and human processes do not directly emit ozone; instead, human activities emit the chemicals that are necessary for the creation of ozone. Ozone is a reactive gas formed in the presence of pollutants emitted from industrial processes and combustion engines (nitrogen oxides and volatile organic compounds).[18] Local weather conditions are closely linked with the formation of ozone. Heat waves and high temperatures can create the optimum conditions for ozone generation, which is considered a summertime issue. Delaware's ozone season begins in April and ends in October, with the peak ozone season being June to August.[19]

The relationships between temperature and ozone creation are well understood. Climate change is expected to increase the intensity of summer temperatures. Increased summer temperatures and longer duration of heat waves may create optimum conditions for increased ozone formation.[20] Seasonal shifts in temperature may also influence ozone concerns in the state of Delaware. The current peak ozone season could be extended if warm temperatures increase in the "shoulder" months, now considered May and September. In addition to high temperatures, future increased emissions could also drive ozone formation during the peak ozone season.[21]

Particulate Matter

Particulate matter is a type of air pollution composed of small solid and liquid particles that are suspended in the air, many of which are invisible to the naked eye. The particles vary in chemical makeup and composition. Particulate matter is characterized based on the size of the particle. Two categories are important when considering human health impacts: particulate matter 10 or (PM_{10}) and particulate matter 2.5

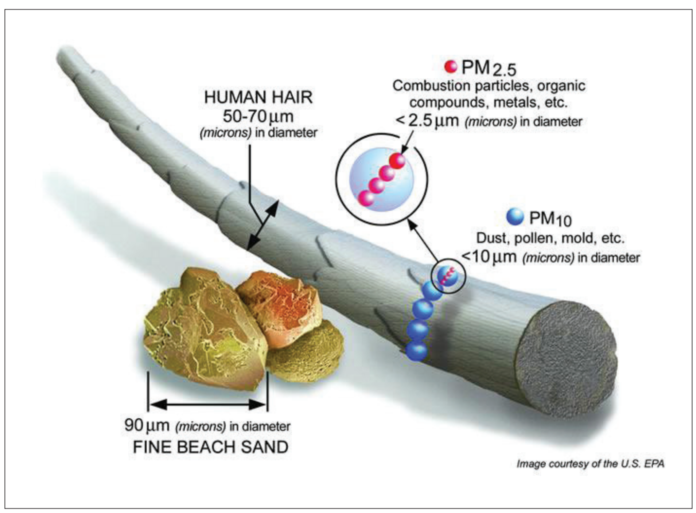

Figure 5.3 Size comparison of particulate matter. Source: U.S. Environmental Protection Agency.

($PM_{2.5}$) – also referred to as coarse or fine particles (**Figure 5.3**). "Inhalable coarse particles"(PM_{10}) are generated from suspension of dust, soil, other soil-like materials (e.g., dust or materials from roads, windstorms, mining, and volcanoes), pollen, mold spores, and sea salts.[24] "Fine particles" ($PM_{2.5}$) can form in the atmosphere through chemical reactions or be released in various chemical and industrial processes such as emissions from vehicles, power plants, and industrial facilities.[25] (PM_{10} is defined as particles that are larger than 2.5 micrometers (µm) but smaller than 10 µm. $PM_{2.5}$ is defined as particles that are smaller than 2.5 µm.)

Particle pollution is also known to be harmful to human health. Particles can enter the lungs and cause respiratory irritation and, depending on their size, can enter into the bloodstream, leading to impacts on cardiovascular health.[26] Coarse particles (PM_{10}) have been shown to increase asthma attacks and decrease lung function. Fine particles ($PM_{2.5}$) are small enough to work their way deep inside lung tissue. Research has shown that prolonged exposure to fine particles can cause respiratory problems, such as decreased lung function, and cardiovascular problems, such as irregular heartbeat and heart attacks.[27]

The linkages between climate change and particulate matter are not as well understood as the linkages with ozone. Particulate pollution is linked to human activities and environmental conditions. Extreme temperature may drive increases in both coarse and fine particle concentrations through increases in combustion processes that burn fossil fuels, increases in wildfire events, and changes in weather patterns that transport particles in the air.[28]

Mold and Pollen

Allergies caused by molds and pollen are a common complaint throughout the United States. Mold is a living organism and therefore is sensitive to changes in environmental conditions, including temperature and precipitation. Pollen is a fine powdery substance produced by plants that can be released in the wind or transmitted to humans. Both mold and pollen can trigger allergic reactions in humans. Understanding the linkages between climate change and allergic illnesses is a focus of ongoing research. The US EPA found in their 2008 study on allergens and climate change that pollen production is expected to increase in many parts of the United States, because the timing of spring bloom will be earlier for many species that trigger allergic reactions. The study also found that pollen and mold content may be more potent in some species as environmental conditions become more favorable for plant growth and reproduction.[29]

The U.S. Global Change Research Program found that in certain areas, if climate projections are correct (increased temperatures, carbon dioxide, and precipitation) many plants will likely have increased growth and productivity.[30] Delaware's projections show that the growing season could lengthen from the current average of around 210 days per year to around 240 days (lower scenario) to 260 days (higher scenario) by the end of the century. This extension of the growing season will affect pollen production and increase the exposure to those populations sensitive to pollen.

Increasing amounts of carbon dioxide (CO_2) in the environment have been shown to increase plant productivity. This includes plant species that are well known to cause allergic reactions. Studies conducted on common ragweed found that higher levels of CO_2 and rising temperatures increased pollen production.[31] One experimental study found that the levels of CO_2 projected in the latter part of the 21st century increased ragweed pollen production by 131 to 320 percent.[32] Climate change could have multiple impacts for sensitive populations by lengthening pollen seasons, increasing pollen production and intensity, and introducing airborne allergens from new plant species.[33] These impacts may increase chronic allergy illness, health care costs, and absences from school and work related to respiratory illnesses.

Changes in temperature and precipitation may lead to more favorable environmental conditions for mold growth and reproduction. Indoor air quality may be degraded as temperature and humidity increases, especially those spaces without air conditioning or dehumidification

Air Quality Index

The Air Quality Index (AQI) was created to inform the public of their surrounding air quality. A daily air quality reporting system was required in the 1977 amendments to the Clean Air Act and, after a name change in 1999, the AQI became the nationally recognized measure of air quality in the United States. Today, the US EPA and the Delaware Division of Air Quality, along with agencies in more than 300 major U.S. cities, work together to provide the daily air quality announcements as well as air quality forecasts. The AQI tracks the following air pollutants, all of which can be harmful to human health: ozone, particulate matter, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Daily monitors from across the country gather data on pollutants and send the information to the US EPA, where scientists run formulas to turn that data into the AQI value for that day. Cities and local air boards can also provide air quality forecasts to allow residents to plan for the coming day(s).

Air Quality Index (AQI) Values	Levels of Health Concern	Colors	Implications for Public Health
When the AQI is in this range:	... air quality conditions are:	... as symbolized by this color:	
0 to 50	Good	Green	Air quality is satisfactory and poses little or no health risk.
51 to 100	Moderate	Yellow	Air quality is acceptable, but may pose a health concern for people who are especially sensitive.
101 to 150	Unhealthy for Sensitive Groups	Orange	Air quality may pose concerns for those who have sensitivities to air pollution.
151 to 200	Unhealthy	Red	Air quality is compromised and everyone may begin to experience health effects.
201 to 300	Very Unhealthy	Purple	Air quality is very unhealthy and everyone may experience more serious health effects.
301 to 500	Hazardous	Maroon	Air quality is hazardous to human health. The entire population is more likely to be affected by serious health effects.

Source: This table was adapted from the US EPA's Air Quality Index and levels of health concern.

The AQI is an index that runs from 0 to 500, with 0 being the lowest level of pollution and 500 the highest. The higher the AQI number, the higher concern for human health. Generally, the level 100 corresponds to the national air quality standards that the US EPA has determined to be an acceptable level to protect human health. An index over 100 for a pollutant is considered to be unhealthy. Often there may be more than one pollutant at levels that are harmful to human health. If this is the case, the pollutant with the highest AQI value is reported for that day with a note about other pollutants that have harmful levels. Colors assist in communicating the AQI for the given day. The graphic below shows the AQI levels along with the implications for public health.[22]

The Delaware Division of Air Quality is taking active measures to monitor and alert Delawareans on the impacts of air quality by providing daily air quality alerts and forecasts for the state. The Delaware Air Quality Monitoring Network[23] allows residents to receive real-time air quality data throughout the state. The Division of Air Quality also works with surrounding states, planning organizations, and the US EPA on large-scale programs to control and prevent air pollution, including tougher emission controls on emitters of the heaviest pollution loads, cleaner-running cars, and vehicle emission testing programs. These measures are assisting in reducing air pollution throughout the state and making the air easier to breathe.

capabilities. These spaces could experience increasing incidences of mold growth and decreases in human respiratory health. Studies have suggested that extreme events that cause flooding could increase conditions for mold growth, especially in the presence of high humidity. Studies conducted after Hurricane Katrina found that mold growth increased in flooded buildings and spaces. For sensitive individuals, these changes can cause increased or prolonged allergic reactions.[34]

5.3.2. Diseases

The spread and transmission of diseases are shaped by the environment, climate, and human interactions. Seasonal patterns influence the diseases (viruses, bacteria, parasites, etc.), the mechanisms by which they spread (mosquitoes, ticks, etc.), and the exposure (spending time outdoors, swimming, etc.). Though all of these interactions are complex, changes in climate may influence the incidence of disease, the geographic distribution, and periods of exposure to diseases that harm human health.

Vector-Borne Diseases

Vector-borne diseases (VBD) are transmitted from the infected bite of one organism (mosquitoes, ticks, fleas, mites, etc.) to humans and/or other animals.[35 36] Vector-borne diseases are some of the world's most problematic, including malaria, plague, West Nile virus, dengue fever, and the most common VBD in the United States, Lyme

Table 5.1 Mosquitoes and vector-borne diseases in Delaware

Disease	Mosquito Vector (scientific name)	Vector Characteristics
Dengue fever	yellow fever *(Aedes aegypti)*	primary vector for dengue in far southern U.S.
	Asian tiger *(Aedes albopictus)*	a primary vector for dengue in southeast Asia; only a minor vector to date for dengue in far southern US
Malaria	common malaria *(Anopheles quadrimaculatus)*	common in Delaware, capable of causing locally transmitted malaria if malaria-infected humans are present
West Nile virus (WNV)	Asian tiger *(Aedes albopictus)*	a minor vector to date for WNV
	common house *(Culex pipiens) (*northern subspecies) *(Culex quinquefasciatus)* (southern subspecies)	primary WNV vector for humans
	unbanded saltmarsh or little sal *(Culex salinarius)*	brackish marsh relative of common house mosquito, secondary vector for WNV
	white-dotted *(Culex restuans)*	primary vector for WNV among birds
	cedar swamp or black-tailed *(Culiseta melanura)*	primary vector for WNV among birds
	encephalitis *(Culex tarsalis)*	primary vector for WNV among birds
Eastern equine encephalitis (EEE)	cedar swamp or black-tailed *(Culiseta melanura)*	primary vector for EEE among birds
	cattail or irritating *(Coquilletidia perturbans)*	freshwater vector for EEE in humans
	floodwater *(Aedes vexans)*	freshwater vector for EEE in humans
	brown saltmarsh *(Aedes cantator)*	secondary vector for EEE in humans
	common saltmarsh *(Aedes sollicitans)*	primary vector in Delaware for EEE for humans
St. Louis encephalitis (STE)	common house *(Culex pipiens)(*northern subspecies) *(Culex quinquefasciatus)* (southern subspecies) Other species, including some *Culex, Aedes, and Coquillettidia,* can be vectors	primary vector *(Culex pipiens)* in Delaware for STE for humans
La Crosse encephalitis (LCE)	eastern tree hole *(Aedes triseriatus)*	Primary vector for LCE

disease.[37] The vectors, the diseases, the hosts, and the environment all have complex interactions that make predicting and modeling vector-borne disease spread difficult.[38]

Mosquitoes transmit a variety of diseases known in the United States (**Table 5.1**), such as West Nile virus and encephalitis, as well as diseases more commonly found in the tropics, such as malaria and dengue fever. Historically, the Mid-Atlantic was prone to outbreaks of malaria; however, advances in detection, public health, water purification, and medical treatment have decreased occurrences of malaria in the region.[39] Other tropical diseases are not endemic to Delaware, although they can occur as the result of travel outside of the region or country.[40]

Delaware is considered a hot spot for mosquito activity.[41] This is primarily because the large amount of wetlands (coastal and freshwater) throughout the state and high population densities along the coast lead to higher rates of exposure. Of the 57 species of mosquitoes found in Delaware, 19 are identified as problematic. Problematic mosquitoes are those that act as the vector for disease or are considered to be an aggressive nuisance to humans as well as other mammals and birds. Mosquito season in Delaware ranges from mid-March to late October or early November. During this time, mosquitoes are most prevalent and environmental conditions are optimal for breeding.[42]

Ticks are another common vector throughout the United States and in Delaware. Ticks are known to spread a variety of diseases, including Lyme disease, spotted fever rickettsiosis, and Ehrlichia, as well as rarer diseases such as tularemia and babesiosis.[43] Lyme disease is the most common tick-borne disease in the United States and in Delaware. In 2011, the CDC reported just over 24,000 cases of Lyme disease in the United States[44]; this includes 874 reported cases in the Delaware.[45] It is important to note that Lyme disease can go undetected and is underreported in the United States. The CDC also estimates that in 2011 there were another 8,700 probable, but not confirmed, cases of Lyme disease in the United States, including 106 probable cases in Delaware. Delaware's rate of incidence is 84.6 confirmed cases per 100,000 population, the highest in the nation.[46] **Table 5.2** lists common tick-borne diseases that have been reported in Delaware and the species of ticks that carry the disease.

The interactions among the vectors, diseases, and hosts are complex, as are the impacts of climate change, including increasing temperatures and changes in precipitation patterns. Warmer average temperatures may hasten pathogen and vector development and increase survivability. Geographic ranges may shift for both the vector and the pathogen, leading to emergence of diseases in new areas. Changes in temperature and precipitation increase duration of infectiousness, allowing for increased periods of transmission and outbreaks of disease. However, increased awareness of the diseases, improved public health infrastructure, and monitoring and control of the vectors are likely to prevent large-scale outbreaks in the United States.[47]

Table 5.2 Ticks and vector-borne diseases in Delaware

Disease	Vector
Lyme disease	blacklegged tick (also known as deer tick) *(Ixodes scapularis)*
Rocky Mountain spotted fever	wood tick (also known as American dog tick *(Dermacentor variabilis)* brown dog tick *(Rhipicephalus sanguineus)*
Babesiosis	blacklegged tick *(Ixodes scapularis)*
Ehrlichiosis/ anaplasmosis	lone star tick *(Amblyomma americanum)* blacklegged tick *(Ixodes scapularis)*
Tularemia	wood tick *(Dermacentor variabilis)* lone star tick *(Amblyomma americanum)*
Powassan encephalitis	blacklegged tick *(Ixodes scapularis)*

Water- and Food-Borne Diseases

Water and food-borne pathogens are a current issue of concern, and climate change has the potential to increase the spread of and exposure to these pathogens. Waterborne pathogens affect human health via drinking water contamination and skin contact with contaminated waters. Waterborne diseases can contaminate food through application to fresh produce and in waters that affect seafood. The CDC estimates that each year 1 in 6 people in the United States, roughly 48 million people, will be sickened by consuming contaminated food.[48] The majority of waterborne and food-borne pathogens are bacteria (*Salmonella*, *Campylobacter*, *Vibrio*, and *Leptospira*), viruses (Noroviruses and Rotaviruses), and parasites such as *Crytospridium* and *Giardia*. Incidences of water- and food-borne illnesses are underreported because symptoms are generally short-lived, making quantification difficult.

Water and food safety are complex issues, and climate change may influence many of the variables that lead to increases in water- and food-borne illness.[49] Climate change could increase human exposure to waterborne and food-borne diseases. Increases in precipitation, warmer temperatures, and increasing frequency of extreme events could make water- and food-borne illnesses and outbreaks a more common occurrence.[50 51 52]

The CDC describes several direct and indirect impacts of climate change on waterborne disease. Direct impacts include changes in temperature and precipitation frequency that may change local flood and run-off conditions and affect wastewater treatment facilities. In addition, changes in ocean health could lead to human exposure to neurotoxins from seafood and shellfish.[53] Indirect impacts include changes in ecosystems that may foster increases in pathogens, and extreme events that would result in decreased water quality and allow pathogens to proliferate.[54]

Research has found a strong correlation between outbreaks of waterborne illness and extreme rainfall event. Increases in pathogens in untreated, surface, and groundwater have been documented across the nation.[55] Increased precipitation creates pathways for pathogens to spread, increasing contamination risks in drinking and recreational waters as well as water used to process fresh foods and shellfish. Increased temperatures could increase pathogen survivability and geographic range of the microorganisms. Temperatures may also influence the developmental cycles of vectors that may spread the pathogens. The CDC's Climate Change Science Program has noted a strong association between sea surface temperatures and the proliferation of many *Vibrio* bacteria species, including the species that causes cholera. The CDC has suggested that rising temperatures would lead to increased occurrences of *Vibrio*-related illnesses.[56]

Wastewater treatment infrastructure is often where extreme events can increase exposure to waterborne pathogens. Combined sewer system (systems that treat both storm water and wastewater) treatment facilities are currently affected by extreme precipitation events, which can overwhelm these systems, causing backups and/or overflows, leading to contamination of surrounding surface waters. Combined sewer systems are found throughout Delaware, and several have been known to back up and overflow during precipitation events. Onsite sewage treatment facilities (septic systems) may fail due to high water tables and/or repeated flooding. Septic system failure or malfunction may release bacteria and pathogens, leading to contaminated surface and/or ground water. Coastal areas may also have the compounded risk of septic systems and sea level rise. (Note that water infrastructure is also discussed in the water resources chapter [6].) Urban and rural runoff serves as an additional pathway for surface water contamination. Pathogens can enter water systems through runoff from agricultural operations and livestock operations as well as urban sites contaminated with chemicals or other waste.

5.3.3. Risk Factors

Certain populations and communities have higher risks of climate-related incidents. The risks related to temperature, air quality, and disease vary depending on certain risk factors that include age, socioeconomic factors, underlying health conditions, and degree of exposure. Special attention must be given to these risk groups, changes in these populations, and development patterns when considering adaptation or intervention measures related to future climate change and climate impacts.

Age

Infants, children, and the elderly are of particular concern. Children's small body size can limit their ability to deal with high heat or cold. In addition, young children's nervous system is not fully developed, furthering hampering their ability to cope with extreme temperature.[57] Children often do not recognize the symptoms of exposure and may have increased sensitivities to air pollution because of time spent outside. Elderly people also have difficulty regulating their core body temperature due to a reduced ability to sense extremes. In addition, the elderly are more likely to have chronic diseases or underlying health problems.[58]

In Delaware, population projections show that overall the population is graying. It's estimated that by 2040 almost a quarter (24 percent) of the population will be over the age of 65. In 2012, around 15 percent of the population was over age 65. Population projections show that the number of children under the age of 10 is expected to decrease slightly on a percentage basis from 12 percent to 11 percent.[59] These shifts in population, along with increasing temperatures, may have public health impacts on populations identified to be sensitive to extreme temperatures.

Socioeconomic Factors

People living in poverty are especially vulnerable to health risks related to climate. Low-income individuals who lack access to heating and/or cooling, medical assistance and care, and/or live alone are all considered to be at risk to temperature extremes. Socioeconomic factors also play a role in displacement after extreme events. People of lower socioeconomic standing can often not afford to or do not have the resources to rebuild in the existing community. In addition, they often have difficulties regaining the livelihoods that they had prior to the event. Migration can also be an issue with low-income communities post-event. Many people and households will choose to permanently relocate instead of returning to their home community. This can lead to mental health distress and/or stress-related disorders.[60] According to the 2010 U.S. Census, there are currently 102,700 people (11.2 percent) in Delaware living below poverty level.[b] These populations may struggle to cope with changes in temperature, precipitation, and extreme events.

Underlying Health Conditions

Underlying health conditions, such as heart and lung diseases, diabetes, and autoimmune disorders, can impair the body's response to extreme temperature, as well as vector-, water- and food-borne illness. These impacts may aggravate the underlying conditions, leading to illness or death. Individuals who are obese and those with limited physical fitness can be at high risk for temperature-related problems. In addition, certain medications that may be used to treat the underlying condition may reduce the body's ability to maintain a steady core temperature by obstructing blood flow or inhibiting mineral and fluid balance. [61]

Exposure

People who work or spend time outdoors may be at risk to extreme temperatures and to diseases. Workers who spend a great deal of time outside during the summer months are more likely to experience a temperature-related illness (heat stroke or frostbite) or dehydration. In urban areas, individuals who live in the upper floors of buildings but do not have access to temperature controls can also be at risk for extreme temperatures. This is most notable with the urban heat island effect and lack of air conditioning.

Children and adults who spend time outdoors have a greater exposure to air pollution, which can affect their respiratory system and increase sensitivity. Outdoor recreationalists who spend time in wooded areas or parks have greater exposure to vector-borne diseases such as Lyme disease and West Nile virus. In addition, those people who recreate in untreated water bodies (nonchlorinated or underchlorinated) can have increased exposure to waterborne diseases.

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b Poverty level is defined by the U.S. Department of Health and Human Services and is based on income and household size guidelines. For Delaware, 2013 poverty guidelines are, for a family/household of four people, a household income of $23,550. See http://aspe.hhs.gov/poverty/13poverty.cfm#guidelines for additional information on poverty guidelines.

5.4. Potential Impacts of Climate Change to Delaware's Public Health

5.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The **lower scenario** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The **higher scenario** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century (**Figure 5.1**).

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

- Heat waves, or consecutive days with sustained high temperatures, are expected to increase. Heat wave events in which temperatures are over 95°F are projected to average 12 days (lower emission scenario) to 25 days (higher emission scenario). Hundred-degree (100°F) heat wave events over the next century could average around 4 days under a lower scenario and 13 days under a higher scenario (**Figure 5.4**).

Precipitation Changes

- Average precipitation is projected to increase by and estimated 10 percent by end of century, consistent with projected increases in mid-latitude precipitation in general.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

5.4.2. Potential Impacts to Public Health

- Delawareans' exposure to increased temperatures is projected to increase over the next century- especially in the summer months. Human health is directly affected by high heat. Delaware is likely to confront an increase in heat-related mortality and morbidity.

- Delawareans at risk to heat: Communities and individuals who are economically disadvantaged and/or have underlying illnesses may have increased impacts related to heat stress. Urban communities – specifically those without access to cooling – may suffer from increased impacts due to heat island effects.

- Delaware's air quality may continue to degrade as conditions for ground level ozone increase (increased temperatures and heat waves). It is likely that without additional regulations or policies to control the pollutants that cause ground level ozone, concentrations will increase and affect the health of people living in Delaware.

- Increasing precipitation and temperatures may lead to conditions that are ideal for increased exposure to allergens and mold as well as pathogenic diseases. Relationships among the environment, organisms, and diseases are complex; however, increases in ideal breeding conditions (temperature and precipitation) or habitats for harmful organisms may increase human exposure.
- Risk factors play a strong role in community health as well as in individual health.

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Chapter 6 – Water Resources Summary

Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower emissions scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

Precipitation Changes

- Precipitation is projected to increase, particularly in winter.

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events (**Figure 6.1**), indicating an increase in precipitation intensity.

Potential Impacts to Water Resources

- ***Water supply and demand*** will be affected by rising temperatures and potentially more frequent droughts, especially in summer months. Water demands for both domestic and public water supply as well as irrigation water peak in summer months. As average temperatures increase, the period of peak demand may lengthen as the warm summer temperatures

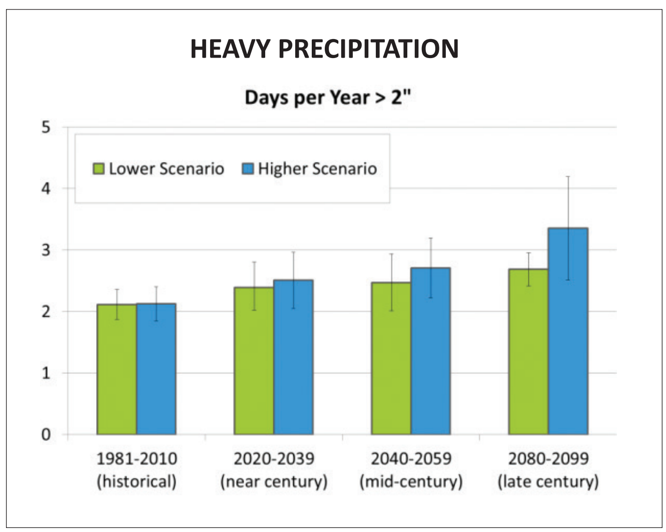

Figure 6.1. Records across 14 Delaware weather stations show that on average the state currently experiences approximately 2 days per year with more than 2 inches of precipitation. By end of century, these numbers are projected to increase by +0.5 to 1 days per year with more than 2 inches of precipitation. Source: Hayhoe et al. (2013).

develop earlier in the year and extend later into the autumn.

- ***Water quality*** may be affected by sea level rise and changes in precipitation, including droughts and extreme rain events. Salinity in tidal reaches of rivers and streams may be affected by climate change impacts. Extreme weather events and flooding can increase runoff and pollutant transport, resulting in contaminated surface water and groundwater.

- Climate change impacts are likely to magnify risks for Delaware's ***water infrastructure***, including public water supply, wastewater treatment, individual wells and septic systems, stormwater systems, and water storage and flood control structures. With the projected increase of more intense rain and storm events, water infrastructure will be increasingly strained to manage peak flows that may exceed their design specifications. Sea level rise and increased flooding associated with extreme rain events may result in structural or operational damage to dams, levees, impoundments, and drainage ditches.

- ***Public health and safety*** are challenged by Delaware's flooding and drainage problems, both in coastal areas and inland floodplains. Climate change impacts associated with sea level rise and extreme rain events are likely to result in more frequent and extensive flood problems that compound or magnify other stressors.

Chapter 6
Water Resources

Chapter Contents

- Overview of Delaware's freshwater resources, both surface water and groundwater
- Summary of climate change impacts that pose challenges to water resources throughout the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to water resources (nonclimatic impacts to resources)
- Potential vulnerabilities to water resources in Delaware (based on current research and expert interviews – statewide scope)

This chapter focuses on the current and potential impacts of climate change on Delaware's freshwater resources. These include developed water sources and infrastructure used for public supply, agriculture, and industry, as well as aquatic resources and natural habitat. Both water supply and water quality issues are addressed. Note that climate change impacts to aquatic ecosystems are discussed further in Chapter 8, Ecosystem and Wildlife, of this Assessment.

6.1 Overview of Delaware's Freshwater Resources

6.1.1. Freshwater Resources and Uses

Delaware has relatively high annual precipitation (average 45 inches per year), distributed fairly evenly throughout the year. In addition, geologic conditions in Delaware are good for storage and recharge of significant groundwater supplies. As a result, the state enjoys plentiful freshwater resources from both surface and groundwater sources.

North of the Chesapeake and Delaware Canal, 70 percent of public water supplies is obtained from surface water resources and 30 percent is obtained from groundwater resources. South of the canal, all water used for public and domestic supply and more than 98 percent of water used for irrigation is obtained from groundwater resources.[2] Freshwater withdrawals in Delaware (from both surface water and groundwater sources) totaled over 600 million gallons per day (mgd) in 2005 (**Figures 6.2** and **6.3**).[3] According to water use data from the U.S. Geological Survey, nearly two-thirds of freshwater withdrawals were used for thermoelectric energy production (nonconsumptive use of water for cooling).[4] (Note that both surface freshwater and saline water are used in thermoelectric power production; no groundwater is used for thermoelectric.) One-third of freshwater withdrawals – approximately 200 million gallons per day (mgd) – is used primarily for public supply (96 mgd), irrigation (65 mgd), and industry (42 mgd).

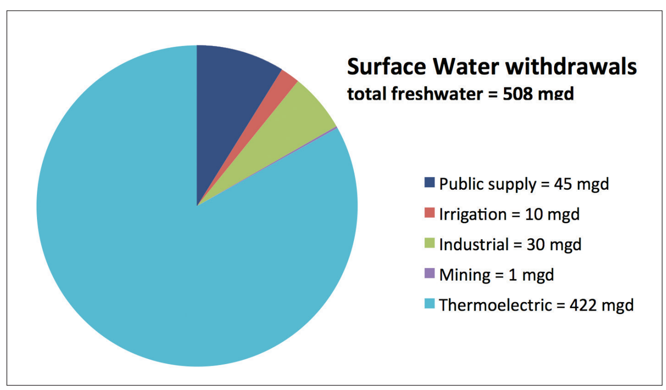

Figure 6.2. Surface freshwater withdrawals in Delaware. Source: USGS 2005.

Surface Fresh Water

Delaware has four major drainage basins: the Chesapeake Bay, Delaware River and Bay, Delaware Inland Bays, and Piedmont watersheds. The Christina River and Brandywine Creek are important tributaries in the Piedmont watershed that provide surface water supply for drinking water and industrial use in the northern part of the state (**Figure 6.2**).

Surface water supplies can be vulnerable to severe shortages under drought conditions. In 2002, the worst drought on record hit Delaware, with significant impacts in northern New Castle County. Streamflows reached a record low for the county with brackish, waters encroaching into freshwater areas such as the tidal portions of White Clay Creek and Christina River. In response, the Delaware Water Supply Self-Sufficiency Act (House Bill 118) was passed into law in July 2003.

Under the act, water utilities had to ensure there were sufficient sources of water supply to withstand another 100-year drought like that of 2002. In addition, the state and private water suppliers invested in increasing water storage capacity through several large infrastructure projects.

Groundwater

Groundwater is the primary water source (**Figure 6.3**) for southern New Castle County and most of Kent and Sussex Counties. Ten major aquifers are found in Delaware, both confined and unconfined. The Columbia Aquifer is the most heavily used for public and domestic water supply and irrigation. As an unconfined surficial aquifer, it is highly susceptible to contamination. Maintaining base flow of groundwater is important, because it is also a major supplier of water to streams. In times of drought, almost all surface water flow comes from groundwater discharge. Therefore, preventing overdraft[a] of aquifers is essential to maintaining surface water supplies that provide much of the state's water.

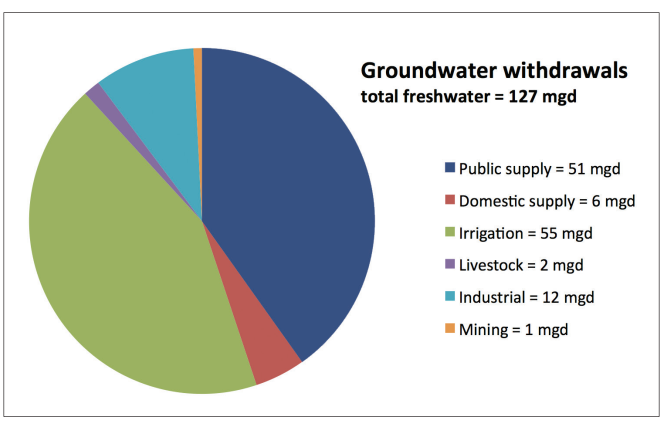

Figure 6.3. Groundwater withdrawals in Delaware. Source: USGS 2005.

The seasonality of water demands is significant in Kent and Sussex Counties. Water demand increases in the summer because of irrigation needs for farming and landscaping and the increased population of vacationers and summer residents. This stress on water resources is compounded because the increased demand coincides with lower groundwater levels, a result of increased evapotranspiration rates and reduced rainfall.

Freshwater Aquatic Resources

Delaware has more than 2,500 miles of rivers and streams and 3,000 acres of ponds and lakes.[5] Additionally, wetlands cover as much as a quarter of Delaware's land area. The recently published wetlands inventory and assessment report, "Delaware Wetlands: Status and Changes from 1992 to 2007,"[6] revealed that total wetland acreage continues to be lost in Delaware. Continued losses of wetlands will have important consequences for the state's water quality.

Wetlands provide critical ecosystem services, including flood control by mitigating the effects of severe storms by absorbing precipitation; protecting coastal property and ecosystems from storms; providing groundwater flow; filtering contaminants from surface and groundwater; and providing habitat for a range of flora and fauna.

The Delaware River is a significant water resource that provides a wide range of economic and environmental benefits to the citizens and businesses in the state and region. The river's watershed encompasses 13,539 square miles, including portions of New York, Pennsylvania,

[a] Groundwater overdraft refers to withdrawals of groundwater from an aquifer at rates considered to be excessive and that may lead to declining groundwater levels, increased pumping costs, deterioration of water quality, and reduction of water in streams and lakes.

New Jersey, and Delaware. The river provides drinking water for a population of 16 million people, including 8 million who live in the basin and 8 million who live in northern New Jersey and New York City. The Delaware River provides critical water supply for industry and thermal energy production and serves as a major transportation corridor for shipping, linking the Atlantic Ocean to the Port of Wilmington, the Port of Philadelphia, and the Chesapeake Bay via the Chesapeake and Delaware Canal. (Aquatic habitats, wetlands, and rivers are discussed further in Chapter 8, Ecosystems and Wildlife.)

6.1.2. Water Infrastructure

Water infrastructure in Delaware includes a wide range of systems and structures built and operated for many purposes:

- Public water supply systems provide drinking water through pumping, storage, treatment, and distribution infrastructure.
- Individual domestic wells provide water supply to rural households; wells also provide nonpotable water supplies for farm, nursery, and golf course irrigation.
- Wastewater systems provide collection, transport, and treatment of wastewater from municipal, residential, and industrial sources.
- Septic systems and community on-site wastewater treatment systems are widely used in subdivisions and rural areas not connected to public wastewater systems.
- Stormwater systems, including sewers and drainage structures, manage surface water runoff from rain and snowmelt.
- Dams, dikes, and ditches include structures built to control or channel surface water and provide flood protection.

Public drinking water supply in Delaware is provided by a network of 486 public water systems managed by municipal- and investor-owned utilities.[7] More than 80 percent of Delaware residents obtain their water from community sources, which include municipal supplies, private water companies, or shared groundwater wells. Over half of the state's drinking water is supplied through four major providers: the City of Wilmington Department of Public Works, Artesian Water Company, Tidewater Delaware, and United Water Delaware. Some water utilities in Delaware provide both drinking water and wastewater services. Wastewater treatment systems are managed by both public and private entities. There are 30 public wastewater treatment facilities, with more than 600 pumping stations in Delaware.

Water and wastewater systems have extensive underground pipe networks that can be subject to leakages and breakage, resulting in sewage spills and contamination of water supplies. Aboveground infrastructure can also be vulnerable to flooding and extreme weather events that affect the function of storage tanks, pumping stations, sedimentation and aeration tanks, filters, and other structures. Water and wastewater infrastructure requires continual monitoring; system managers must be able to respond quickly to system damage or failures to ensure water service that is reliable and safe.

In rural areas of the state, many households are not connected to public or community water or wastewater systems; these homes rely on individual domestic wells for drinking water supply and on septic systems for wastewater disposal. Individual wells are typically less than 100 feet in depth and tap into shallow groundwater, making them more vulnerable to groundwater contamination than deep water wells. There are approximately 78,000 septic systems statewide, with approximately half of these in Sussex County.[8]

Stormwater infrastructure provides a critical function in diverting surface runoff from rain and snowmelt from paved surfaces and structures and reducing flooding impacts during storm events. Stormwater drainage systems are built to manage the quantity and distribution of runoff; some systems also provide additional benefits such as erosion control or groundwater recharge.

Stormwater can cause physical damage, from scouring or erosion, and is also a significant water quality challenge, as water picks up pollutants as it travels across paved surfaces, farm fields, and suburban lawns. Stormwater infrastructure includes inlets, storm sewers, and outfalls. Inlets are openings in road pavements to divert stormwater into underground sewer pipes. Stormwater exits the system through an outfall, which is typically a pipe outlet made of concrete, metal, or plastic. Outfalls may deposit stormwater directly into a water body, such as a stream or bay, or may convey stormwater into a ditch, swale, or constructed wetland. Stormwater wetlands may be integrated into the system as "green infrastructure," removing pollutants through settling and biological processes.[9]

Water infrastructure in Delaware also includes many structures built to control or channel surface water and provide flood protection. These include dams, dikes, levees, and impoundments. In Delaware, dams are primarily associated with mill ponds that are located inland; dikes are primarily located in coastal regions. Delaware's Dam Safety Program has conducted a statewide inventory of dams and identified 48 dams that are classified as "high hazard" or "significant hazard." (The classification is based on the potential consequences of dam failure, not on the condition of the dam.) Approximately 42 of these regulated dams are managed by the State of Delaware, and many of them are located adjacent to or integrated into state-managed roads and bridges.

Tax ditch channels are another type of infrastructure used for drainage. Tax ditch channels range in size from 6 to 80 feet wide, and 2 to 14 feet deep. A "tax ditch" refers not to the drainage channel itself, but to the legal entity responsible for maintenance of the tax ditch channel. Formation of a tax ditch can be initiated only by landowners who petition Superior Court to resolve drainage or flooding concerns. Delaware has 228 individual tax ditch organizations, ranging in size from 56,000 acres in Marshyhope Creek Tax Ditch in southern Delaware to a two-acre system in Wilmington. These organizations manage more than 2,000 miles of channels, primarily in eastern Sussex and Kent Counties.[10]

Coastal impoundments are areas of upland or wetland habitat where low-level dikes or levees have been constructed to restrict, retain, or exclude water over a selected area.[11] Impoundments provide important breeding and wintering habitat for migratory birds and nursery habitat for fish. In addition, many impoundments also provide flood protection for roads and coastal communities. There are 350 impoundments in the state, encompassing more than 12,000 acres; most are publically owned and managed. (Note that coastal impoundments are discussed in Chapter 8, Ecosystems and Wildlife.)

6.1.3. Water Quality

In almost all of Delaware's watersheds, at least half of the monitored stream segments are classified as impaired (**Figure 6.4**). This means that they do not achieve the regulated water quality standards for certain constituents. The majority of the impairments are for low levels of dissolved oxygen and elevated levels of nutrients (nitrogen and phosphorus) and bacteria. In most cases, the nutrients and bacteria come from nonpoint sources. These pollutants enter surface water through groundwater discharges and as runoff from agricultural and suburban lands, urban stormwater, and wastewater discharges from treatment plants and septic systems. Nutrients, bacteria, and chemical pollutants can pose a serious threat to aquatic wildlife, degrade ecosystem health, and pose health risks to humans.

As required by the federal Clean Water Act, the State of Delaware has established a total maximum daily load (TMDL) for each impaired waterway for nutrient, toxics, and bacteria impairments. More work is underway for toxics as detailed in the Watershed Approach to Toxics Assessment and Restoration Plan.[12] A TMDL is the maximum amount of a pollutant that can enter a waterway without violating water quality standards. Approximately 96 percent of the state is covered by a TMDL regulation. Nonpoint reductions required by TMDLs range from 0 (capping of load) to 85 percent for nitrogen, 0 to

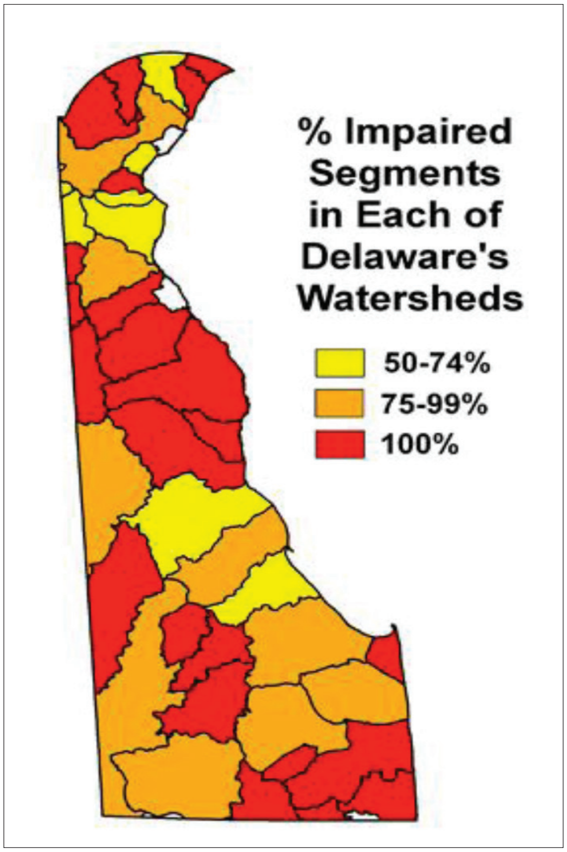

Figure 6.4. Delaware's impaired streams. Source: DNREC Watershed Assessment Section.

65 percent for phosphorus, and 8 to 90 percent for bacteria. In addition, more than 60 organic compounds represent contaminant risks to surface and groundwater supplies, including pesticides, gasoline compounds, solvents, and disinfectant by-products. Trace elements – such as fluoride, lead, and arsenic – also can be found in surface and groundwater. Many prominent streams, including Brandywine Creek, Christina River, Red Clay Creek, and St. Jones River, currently have fish consumption advisories in place due to the presence of toxic compounds such as mercury, dioxin, and PCBs (polychlorinated biphenyls).

6.2. Climate Change Impacts to Water Resources in the United States

6.2.1. National Overview

In recent years, a number of technical reports and policy guidance documents have been developed at the national level to summarize current climate science information and to provide an analytical framework for incorporating climate change considerations into planning processes and policy development. The U.S. Climate Change Science Program has produced a series of synthesis and assessment (SAP) reports (2006-2009) to provide a review of scientific literature on the historical and potential impacts of climate change. In the assessment of water resources (SAP 4.3), the report notes that water managers use various methods to plan for variability in water supplies and changing flows. However, these methods assume that historic observations of streamflow are statistically "stationary." Thus, water systems have been designed for a range of climate variability defined by past streamflow and weather variations. However, research reviewed in the assessment suggests that "in the era of changing climate this assumption is no longer tenable."[13]

In the 2009 interagency report "Climate Change and Water Resources Management: A Federal Perspective," the authors note that climate change is one of many dynamic processes affecting water resources management. Changes in population size and distribution, land use patterns, emerging technologies, and aging infrastructure also must be considered in a "holistic approach to water management." This report also states that "given a changing climate, it may be appropriate to evaluate the system response for a range of hydro-climatic variability wider than in the historic record."[14] In October 2011, the Interagency Climate Change Task Force released the "National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate." One of the recommendations of the plan is to strengthen the assessment of vulnerability of water resources to climate change, stating that "to adapt to climate change, water resources managers must first determine the degrees of risk and vulnerability in their systems."[15]

Climate change impacts are likely to affect water resources in a variety of ways, posing potential vulnerabilities across many sectors, including public health, agriculture, industry, tourism, and infrastructure. **Table 6.1** summarizes the linkages between various types of climate change impacts, affected sectors, and impacts to water supply and water quality.

In January 2013, the U.S. Global Change Research Program released a draft of the Third U.S. National Climate Assessment; the final report is due to be released in 2014. The draft national climate assessment describes a number of climate impacts that affect water resources nationally, as well as in the Northeast region of the United States (including Delaware). The draft

Table 6.1 Climate change impacts to water resources across sectors in the United States

Climate change impacts	*Affected sectors*	*Water resource impacts*
Increased temperatures		
Increased demand for electricity in summer	Energy	Water supply
Increased demand for irrigation water in summer	Agriculture	Water supply
Increased demand for domestic and municipal water use (landscaping, home use)	Public health Tourism and recreation	Water supply
Increased algal blooms and eutrophication ➔ decreased oxygen in bays, rivers, lakes	Wildlife and ecosystems Tourism and recreation (fishing, swimming, boating)	Water quality
Increased water temperatures ➔ heat stress impacts to aquatic species	Wildlife and ecosystems	Water quality
Increased water temperatures ➔ reduced efficiency for industrial cooling water	Energy Industry/energy	Water quality/supply
Increased variability of precipitation ➔ heavy precipitation events		
Overflow from combined sewer systems	Infrastructure Wildlife and ecosystems Public health	Water quality
Contaminated surface water from runoff and pollutant transport	Public health Wildlife and ecosystems	Water quality
Contamination of groundwater recharge areas and wells	Infrastructure Public health	Water quality
Damage to water supply and wastewater treatment systems, including on-site wastewater treatment systems	Infrastructure Public health Wildlife and ecosystems	Water quality
Increased variability of precipitation ➔ droughts		
Reduced surface water supplies	Public health Infrastructure Agriculture Wildlife and ecosystems	Water supply
Increased groundwater withdrawals ➔ groundwater overdraft	Public health Agriculture Industry	Water quality/supply
Sea level rise ➔ coastal inundation, shoreline erosion		
Contamination of surface water and groundwater recharge areas and wells	Infrastructure Public health	Water quality
Damage to water supply and wastewater treatment systems	Infrastructure Public health Wildlife and ecosystems	Water quality
Upstream shift of salt line in the Delaware River	Infrastructure Industry Wildlife and ecosystems	Water quality/supply

assessment reports that, across the Northeast region, annual precipitation has increased by 5 inches (10 percent) between 1895 and 2011. The region has also experienced a greater increase in heavy precipitation events than any other region in the United States, with a 74 percent increase in the amount of precipitation falling in extreme rain events. At the same time, seasonal drought in summer and fall is expected to increase in the Northeast region, as higher temperatures result in greater evaporation and earlier snowmelt in winter and spring.[16] Changes in precipitation patterns also affect streamflow, which can lead to impacts in water supply, water quality, and risk of flooding. In the Northeast and Midwest regions of the country, annual peak flows have increased in the past 85 years. These peak flows, along with soil moisture and other factors, influence the volume of runoff that may contribute to an increase in flooding. Surface runoff, especially when combined with intense precipitation, is increasing loading of sediment, nutrients, and other contaminants in surface waters, resulting in negative impacts to water quality.[17]

6.2.2. Impacts to Water Supply and Water Quality

It is important to note that water quality and water supply are strongly linked. For example, contamination of surface water may render that source unusable for drinking water, reducing supply. In addition, climate change–related impacts to water supply and water quality can have significant economic costs, such as repair, replacement, or relocation of water infrastructure; additional treatment to bring degraded water to safe drinking water standards (increasing cost and energy use); and declines in tourism due to beach closures or flood-damaged recreational facilities. Climate change impacts that may affect *water supply* include:

- Increased air temperatures, leading to increased water use for public and domestic water supply and irrigation (peak demand in summer);
- Increased water temperatures, potentially reducing efficiency of cooling water for industry and energy production;
- Extreme weather events and flooding, stressing the capacity of and potentially damaging water supply infrastructure;
- Increased variability of rainfall, potentially leading to droughts and surface water shortages;
- Sea level rise, leading to upstream shift in salinity in rivers and streams, potentially affecting water supply for industry and energy production.

Climate change impacts that may affect *water quality* include:

- Increased air and water temperatures, leading to increased algal blooms in surface water and decreased oxygen levels in bays, rivers, and lakes;
- Extreme weather events and flooding, leading to increased runoff and pollutant transport that can contaminate surface water and groundwater recharge areas and cause physical damage to water infrastructure;
- Sea level rise and coastal inundation, posing risk of saltwater intrusion in wells and contamination of groundwater recharge areas;
- Extreme weather events, flooding, and coastal inundation, leading to degradation or loss of wetlands and reduction in the ecosystem benefits they provide as nutrient sinks;
- Extreme weather events and flooding, stressing the capacity of stormwater and wastewater outfalls, causing water to back up and transporting polluted waters to upland areas;
- Increasing precipitation and sea level rise, resulting in failure of septic drain fields as groundwater levels rise.

6.2.3. Impacts to Water Infrastructure

Climate change impacts to water supply and water quality also affect the function and operation of *water infrastructure*. For example, extreme weather events and flooding can stress the capacity of stormwater systems, leading to sewage spills that pose public health risks and damage ecosystems. In particular, increases in heavy rainfall events pose a growing threat to aging infrastructure and systems not designed for higher levels of flow.

Water infrastructure encompasses a wide range of systems that integrates natural resources and human-built structures to produce, transport, or contain water and wastewater. Providing clean and reliable water supplies for domestic and industrial use requires wells, water treatment facilities (for drinking water and wastewater), pumps, pipelines, and distribution systems. The function of these structures depends on the availability of freshwater of sufficient quantity and quality to meet the demand for drinking water, power generation, irrigation, and other uses. In addition, significant effort, engineering, and expense have been invested in infrastructure designed to contain or store water. This includes large water storage structures, such as dams, reservoirs, and impoundments, as well as smaller millponds. Dikes and levees are widely used for flood protection, and canals and ditches across the landscape function to drain wetlands or shunt water from one location to another.

Water storage and flood control structures, such as dams and impoundments, are also vulnerable to climate change impacts. Changes in precipitation, extreme weather events, and sea level rise are expected to affect water infrastructure. Impacts can occur through gradual changes, such as higher average rainfall, that accelerate the deterioration of structures. High-impact events can damage or destroy the structural integrity of dams, levees, and impoundments, leading to breaching events and catastrophic flooding. Dams are classified in terms of their hazard potential relative to the consequences of failure. A "high hazard potential" dam is one that may result in loss of life in the case of failure. The number of high hazard potential dams is growing as a result of increasing development below dams, putting more people at risk. In addition, the average age of dams in the United States is just over 50 years; thus, many dams are considered deficient as a result of aging, deterioration, and lack of maintenance.

Septic systems are highly vulnerable to the impacts of climate change. The increased risk of flooding and higher water table could result in greater risks and impacts to water quality due to malfunction or failure of septic systems. Pathogens present in septic waste are usually attenuated in the soil system. A rising water table might increase the risk of contamination of surface waters, where inadequately treated sewage poses a significant threat to drinking water and human health. These potential impacts are elevated by the risk of flooding from sea level rise and increases in heavy precipitation events due to climate change. The flushing of nutrients and pathogens will deteriorate the coastal ecosystem as well as the functioning of on-site wastewater treatment systems.

6.3. External Stressors

Population growth (**Figure 6.5**) is expected to increase demand for freshwater withdrawals from both surface and groundwater sources. Population growth will also lead to an increasing volume of wastewater that must be treated and discharged.

Increasing demand for irrigation water is driven by economic forces as well as changes in climate and drought patterns. Irrigated acreage has expanded greatly in Delaware over the past 20 to 30 years, and continues to increase. This trend will result in greater demand for freshwater in peak summer

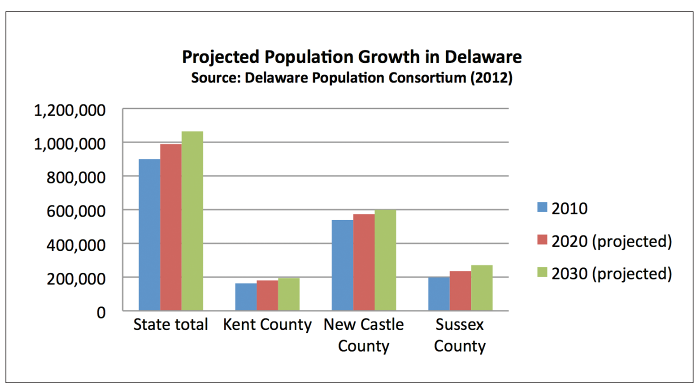

Figure 6.5. Projected population growth in Delaware. Source: Delaware Population Consortium (2012).

months. Increased withdrawals could lead to localized water shortages, overdraft of surficial aquifers, or impacts to local streams and wetlands.

Land use changes that accompany population growth have direct and indirect effects on water resources. Impacts associated with an increase in impervious surface have been widely studied. Impervious surfaces – buildings, concrete, and pavement – alter natural hydrology, resulting in higher volumes of stormwater runoff, increased erosion, and more frequent flooding. In addition, impervious surfaces can affect groundwater levels by impeding recharge.

Impervious surfaces change the natural flow of water (hydrology), because water moves faster over the hard surfaces, resulting in less time and opportunity for vegetation to trap and take up pollutants and water. Loss of vegetation along streams and waterways as a result of development can also increase water temperatures in streams and rivers, which can harm fish and invertebrate species and trigger algal blooms. Water quality in Delaware is already challenged by excess nutrients from a wide range of sources, including wastewater treatment plants, septic systems, agricultural runoff, pet waste, and fertilizers used in urban and suburban landscaping.

Energy costs of water treatment and distribution are a significant economic stressor for water utilities. Water pumping and transport accounts for a large portion of energy use, both in water systems that rely on groundwater and surface water sources. The U.S. Environmental Protection Agency estimates that 4 percent of national electricity consumption annually is used in water processing and transport, and accounts for as much as 75 percent of the cost of providing water service.[18] Energy consumption and costs for water treatment are likely to increase when the water quality of source water becomes degraded. For example, flooding events can transport sediment and other pollutants into streams or reservoirs, resulting in higher levels of treatment needed to meet drinking water standards. Saltwater intrusion into surface or groundwater supplies can also lead to higher energy costs for treatment or blending.

Aging infrastructure is an ongoing concern for water utilities and municipalities. National attention has focused on the costs of repair, replacement, and disruption of service caused by failure of water mains and valves. Many water systems have pipes installed during the construction booms of the post-World War II era or earlier. In the eastern United States, many large cities have water infrastructure systems more than a century old. One common problem with aging infrastructure is leakage; this results in water losses that have an economic cost (including the energy cost of treatment and distribution of lost water). In addition, water leakage in wastewater and sewer systems can exacerbate water quality problems and lead to increased soil erosion, which further undermines the structural integrity of the water system.[19]

6.4. Potential Impacts of Climate Change to Delaware's Water Resources

6.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under the higher as compared to the lower emission scenario and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3-4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

Precipitation Changes

- Precipitation is projected to increase, particularly in winter.

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 6.1**).

6.4.2. Water Supply – Increasing Demand

Changes in precipitation patterns – especially droughts – and increasing temperatures will likely have effects on water supply and demand. The Delaware Water Supply Coordinating Council has developed water supply and demand plans for New Castle County and is currently developing plans for Kent and Sussex Counties to project water supply needs through 2030. The University of Delaware Water Resources Agency estimates that potable water demands in Kent and Sussex Counties may increase from 2010 levels of 61 million gallons per day (mgd) to 83 mgd by 2030, based on population growth. This represents the combined total of public water and individual wells.[20]

Water storage capacity for northern New Castle County has increased significantly in response to severe drought in 2002. As a result of a state-level initiative, water utilities in northern New Castle County developed more than 1.8 billion gallons in new water reserve supplies, including the construction of Newark Reservoir, increased capacity in Hoopes Reservoir, and development of aquifer storage and recovery projects. In addition, water conservation efforts have been implemented that have reduced water demands in northern Delaware from a historic peak of 93 million gallons per day (mgd) to 80 mgd. Conservation water rates have helped reduce water demand; many utilities have also improved water efficiency through leak detection and infrastructure repairs. These additional water supplies are expected to meet projected water demands through 2020 even under conditions experienced during the 2002 drought of record.[21]

The University of Delaware Water Resources Agency conducted an analysis of air temperature data for Wilmington Airport and water demand data in New Castle, Kent, and Sussex Counties. Results indicated that water demand increases by 3 percent for every 1 percent increase in air temperature.

At 90°F, peak drinking water demand during 2010 in Kent and Sussex Counties was 58 million gallons per day (mgd). If air temperature is projected to increase by 2°F by 2030 (or 2/90 = 2 percent), then peak water demand may increase by 6 percent to 61 mgd by 2030 due to atmospheric warming. Resources for the Future published a report that concluded a 1 percent rise in air temperature would increase water demand by as much as 3.8 percent.[22] A study in northeastern Illinois concludes that by 2050, future water demand would increase by 9.1 percent with an air temperature increase of 6°F, or 1.5 percent for every degree Fahrenheit.[23] Based on these findings, by 2030 water demands in Kent and Sussex Counties may increase by 35 percent due to population growth as well as by 8 percent due to a projected 2°F or 2 percent rise in air temperature.

6.4.3. Water Quality – Changes in Salinity and Temperature

Water quality may be affected by sea level rise and changes in precipitation that can result in salinity fluctuations in water resources. Freshwater resources may be affected by intrusion or encroachment of salt water in several ways. Sea level rise and storm surge can cause saltwater intrusion into coastal aquifers, affecting local wells. Some Delaware coastal communities have already had to abandon municipal wells due to high chloride levels and develop new wells further inland. The Sea Level Rise Vulnerability Assessment for Delaware assessed domestic, industrial, irrigation, and public wells that could be affected by sea level rise within the projected ranges of 1.6 feet, 3.3 feet, or 4.9 feet of inundation. For example, the Sea Level Rise Vulnerability Assessment estimates that more than 2,000 domestic wells and 25 public wells could be inundated by a 1.6-foot (0.5-meter) sea level rise.[24] Higher sea level rise scenarios would affect more water infrastructure; an estimated 75 public wells could be inundated under 4.9 feet (1.5 meter) of sea level rise.

Salinity in tidal reaches of rivers and streams may also be affected by climate change impacts. The "salt line" in the Delaware Estuary – defined as the 250 milligrams per liter chloride concentration – fluctuates along the tidal portion of the Delaware River as flows increase or decrease. During low-flow conditions, the salt line moves upriver, which can cause corrosive damage to water infrastructure. Movement of the salt line upriver may affect the freshwater tidal portion of the estuary, threatening many species adapted to this habitat. Sea level rise could increase the tidal influence and salinity levels upriver, although increased precipitation could offset the increasing salinity with additional freshwater inflow.[25] The salt line of the tidal saltwater wedge also migrates upstream in coastal rivers and streams during periods of drought, when freshwater inflow decreases. This effect may be magnified with increasing frequency and duration of seasonal droughts, and further exacerbated with sea level rise.

In addition to salinity changes that affect water quality, increasing water temperature can also lead to changes in water quality and water chemistry. For example, peak water temperatures now exceed 86˚F (30˚C) along the Brandywine Creek and Christina River during the summer, which decreases levels of dissolved oxygen necessary for fish and aquatic health.[26] (The potential impacts of

Salinity in Drinking Water – White Clay Creek

Changing patterns of precipitation and sea level rise may affect salinity in White Clay Creek and pose problems for the Stanton Water Treatment Plant (WTP). The WTP has a freshwater intake situated on White Clay Creek near the confluence with Red Clay Creek. Operated by United Water Delaware, the Stanton WTP withdraws up to 30 million gallons per day (mgd).

Streamflow in White Clay Creek is influenced by freshwater inflow from upstream watersheds and the incoming tide from the Delaware Estuary. Reduced snowpack in upper Delaware Basin affects the timing and quantity of flows; periods of summer drought also reduce flows. A minimum streamflow of 17.2 mgd is needed to protect fisheries and creek habitat and to maintain water quality. Data collected during previous droughts indicate that when streamflow falls below the minimum 17.2 mgd for more than 5 to 7 consecutive days, chloride levels in the stream can exceed the 250 parts per million (ppm) drinking water threshold for chloride.[a] Chloride levels are also tidally influenced by the upstream encroachment of the salt line, a trend that may be enhanced with sea level rise. When chloride levels exceed the drinking water standard, the water must be blended with another source of freshwater to dilute the chloride concentration to an acceptable level.

To manage and monitor chloride levels in White Clay Creek, the water utility has installed a tidal capture structure and implemented a chloride monitoring plan. The tidal capture structure is an expandable bladder that inflates at high tide to temporarily impound freshwater, allowing continued water withdrawals. The structure is deflated at low tide to allow downstream flow. The system must be carefully managed to ensure that minimum flows are maintained for fish passage, and to monitor changes in chloride levels.

changes in water temperature and salinity are also discussed in Chapter 8, Ecosystems and Wildlife.)

6.4.4. Water Infrastructure – Flooding and Sea Level Rise

Climate change impacts are likely to magnify risks for water infrastructure that is already in need of repair or replacement. With the projected increase of more intense rain and storm events, water infrastructure will be increasingly strained to manage peak flows that may exceed their design specifications. The U.S. Environmental Protection Agency has developed an assessment tool for water utilities to identify vulnerabilities and potential adaptation actions to reduce the impacts of climate change to the utilities' infrastructure and operations. The decision framework for the tool provides a guide to potential consequences of climate impacts, including revenue or operating income loss; costs of equipment repair or replacement; degradation of source water or receiving water; and community public health impacts.[27]

Sea level rise may also affect the condition and function of many types of water infrastructure. The Sea Level Rise Vulnerability Assessment for Delaware evaluated wastewater infrastructure and identified pumping stations and treatment facilities that could be inundated as a result of sea level rise through the 21st century. The Sea Level Rise Vulnerability Assessment identified 44 pumping stations (7 percent of the statewide total) that could be affected by a 1.6-foot (0.5-meter) sea level rise; an estimated 136 pumping stations (21 percent of the statewide total) could be inundated under the highest scenario of 4.9-foot (1.5-meter) sea level rise.[28]

6.4.5. Public Safety – Flooding

Water infrastructure in Delaware includes dams and reservoirs, levees, impoundments, and drainage ditches. Some of these structures were built more than a century ago and pose challenges for maintenance and repair. Sea level rise and increased flooding associated with extreme rain events may result in structural or operational damage to flood control structures. Over time, exposure to wind, waves, and tides can cause erosion or seepage that weakens the structure, if not properly maintained. In addition, overtopping of dams and dikes during storm events can lead

Aging Infrastructure – City of Wilmington

Like many older urban developed areas in the United States, the sewer infrastructure used today in the City of Wilmington includes an extensive network of combined sewer overflows (CSOs) that carry both sewage and stormwater. CSOs can lead to water quality issues when the combined sewer system cannot handle the volume of flow from stormwater runoff in addition to the baseline sewage flow during a precipitation event. High tides can also prevent CSOs from functioning properly. When Wilmington's combined sewer system is overwhelmed during a precipitation event, untreated sewage and stormwater runoff can be directly discharged into the tributaries of the Delaware River, including Brandywine Creek, Christina River, Silverbrook Run, and Shellpot Creek.

Due to preventive measures taken over the past two decades since regulations were developed for CSOs through the Federal CSO Control Plan, CSO events have decreased significantly in the City of Wilmington. A major expansion of the Wilmington wastewater treatment plant completed in 1997 at a cost of $30 million improved the capacity of the city's combined sewer system. The improvements expanded capture of the CSOs from 49 percent to 70 percent. As a result, water quality has improved in the waterways that receive CSO discharges and CSO incidents are considered a relatively small contributor to overall water pollution.

Increased precipitation, flood events, and storms are likely to exacerbate the challenge and cost of decreasing and/or controlling CSO events, leading to increased water quality impacts from CSOs. Water quality impacts from CSOs may increase under a climate change scenario with increased precipitation, storm events, and flooding. Discharges of untreated sewage and stormwater runoff into Delaware's water resources may occur more frequently and at a great cost to water quality.

to damage or collapse, increasing the risks of severe flooding in communities protected by these structures. Breaching or failure of dikes and levees can also pose water quality risks if the water impounded by the structure contains contaminated sediments, sewage, or other pollutants that could be released or transported in the event of flooding.

Delaware already faces challenges from flooding and drainage problems, both in coastal areas and inland floodplains. Climate change impacts associated with sea level rise and extreme rain events are likely to result in more frequent and extensive flood problems that compound or magnify other stressors. As described above, changes in watershed characteristics such as increased impervious surface area and loss of wetlands and forests are key factors that influence flood risk. The combination of extreme rain events and changes in watershed hydrology may lead to flooding in areas that have not been previously subject to flooding.

Monitoring data show that Delaware is already experiencing changes in streamflows. For example, floods that exceed the 10-year recurrence interval have become more frequent along the Brandywine Creek since the 1970s. During the same period, drought low flows along Brandywine Creek have declined, with a slight rise following the multiyear drought of 1995-2002.[29] **Figure 6.6** shows annual peak discharge on the Brandywine River at Wilmington, Delaware. Changes in the timing, amount, and velocity of peak flows can affect the river or stream corridor, such as by increased erosion and flooding, and can also affect water withdrawals for drinking water, thermoelectric power generation, and industrial uses.

Water and transportation infrastructure is often physically integrated. In Delaware, approximately 42 regulated dams are owned by the State of Delaware, and many have state roads or highways built on top of the dams. In heavy rain events, rising water levels behind the dam can pose a threat of overtopping, which can flood roads on top or adjacent to the dam. In extreme conditions, overtopping of the dam can cause significant

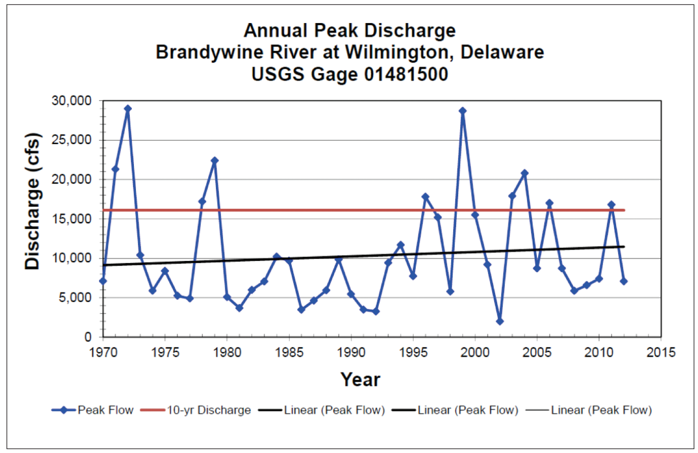

Figure 6.6. Peak streamflows in Delaware (1970-2012). Source: Kauffman (2013).

erosion that weakens the dam structure; in worst cases, erosion or washouts can result in dam failure, releasing huge volumes of stored water downstream at high velocity and causing catastrophic damage.

To prevent overtopping and protect dams from damage, both structural and operational actions can be taken. Erosion protection can involve adding concrete or rock (armoring) to all or a portion of the embankment. Adding a hard surface to a dam structure can also help reduce other impacts to the structural integrity of the dam from seepage, encroachment of roots from woody vegetation, and holes from burrowing animals. Operational measures include opening spillways to lower water levels behind the dam and increasing the spillway capacity. In Delaware, most dams have a single spillway that can be opened by removing boards or opening gates.

In anticipation of Hurricane Sandy, in October 2012, state staff from the Department of Transportation and Department of Natural Resources and Environmental Control coordinated efforts to open gates and remove boards from 30 dams around the state. Monitoring weather forecasts, rain gauges, and water levels provided critical information to determine which dams needed immediate action. As a result, no dams overtopped during the storm.[30] Precipitation and flooding impacts to transportation are also discussed in Chapter 9, Infrastructure.

Flooding poses both economic and safety risks for homes and communities. Costs resulting from flood damages affect homeowners, insurers, and government. More than 200 flood-damaged homes in Delaware have been purchased through government buyout programs since 2000, using local, state, and federal funding. In addition, an estimated $65 million has been spent by state and local governments to address drainage problems resulting from ineffective or inconsistent standards and codes. Flood insurance for property owners in designated floodplains will likely become more expensive.

In an effort to improve floodplain standards across Delaware, a Floodplain and Drainage Advisory Committee was convened in 2011 to recommend proposed standards that would provide more effective flood management and protection than the minimum standards required under the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program (NFIP). The NFIP minimum floodplain standards were set at minimal levels when the program was created, with the expectation that many communities would enact higher standards when needed to better protect public safety and property. The Advisory Committee recommended floodplain and drainage standards that address improved planning, mapping, and land development and building construction. Development standards consider restrictions on development in floodplains to reduce encroachment. Building standards consider freeboard requirements (floor elevations above flood elevations) and guidelines for basements, crawl spaces, and ventilation systems.[31]

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Flood Control Structures – City of New Castle

The construction of earthen dikes along the Delaware River dates back to the late 1600s. The City of New Castle, located directly adjacent to the Delaware River, has four dikes – Buttonwood, Broad Marsh, Gambacorta Marsh, and Army Creek – that protect areas of the city from flooding. These dikes were the focus of a 2011 assessment by the Department of Natural Resources and Environmental Control – Delaware Coastal Programs to evaluate the dikes' condition and develop plans to ensure that the structural integrity of the dikes is sufficient to protect the city against the impacts of coastal storms and rising sea levels.

Overtopping or failure of dikes poses a significant vulnerability for homes and structures in the potential inundation area. Dike failure can result in flooding that is often rapid and forceful, and can occur with little or no warning. The risk of overtopping is increased with the anticipated impacts of sea level rise. Risks of flooding are further exacerbated during extreme rain events, when water enters the protected areas from two sources – river floodwaters and stormwater runoff.

The elevation of dikes can vary over time due to settlement of the structure, impacts of erosion, compaction from vehicle use, and animal burrowing activity. The assessment of the New Castle dikes included measurements of the dikes' lowest elevations compared to flood elevations for 100-year floods, 500-year floods, and projected flood elevations under three sea level rise scenarios for 2100 (0.5-, 1.0-, and 1.5-meter rise). The lowest dike elevations range from 5.5 to 6.0 feet, while flood elevations range from 9 feet for a 100-year storm to nearly 14 feet under the highest sea level rise projection for 2100.[b]

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Chapter 7 – Agriculture Summary

Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

- The growing season is also projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost (**Figure 7.1**).

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

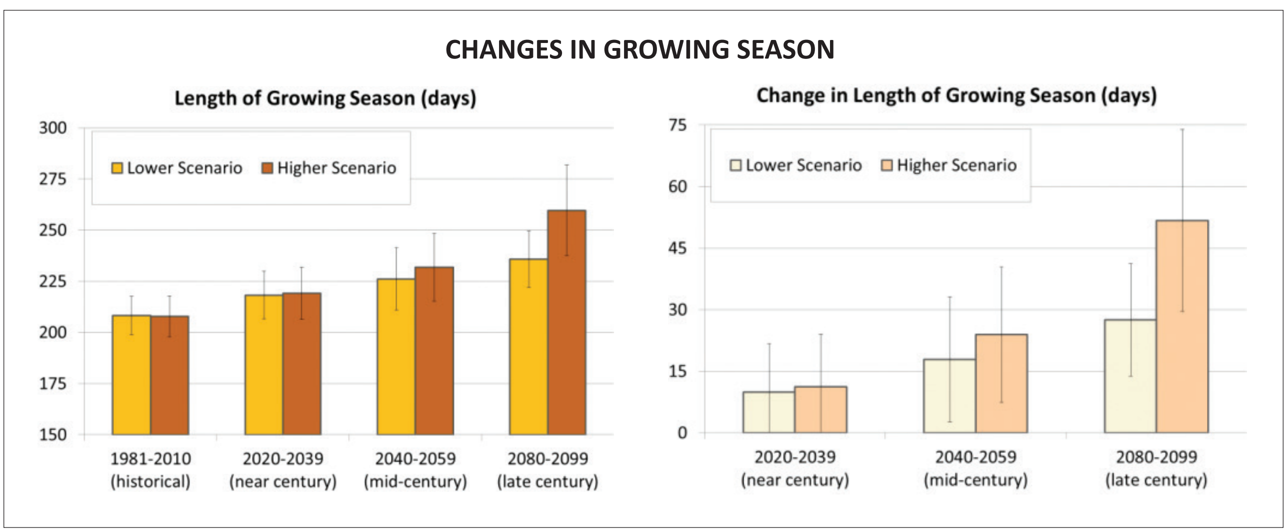

Figure 7.1. The growing season (frost-free days) is projected to continue to lengthen. Differences between the high scenario and low scenario are greater by mid-century and end of century. Source: Hayhoe et al. (2013).

Precipitation Changes

- Average precipitation is projected to increase by an estimated 10 percent by end of century, consistent with projected increases in mid-latitude precipitation in general.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

Potential Impacts to Agriculture

Animal Agriculture

- Heat-related stresses resulting from extreme heat days or sustained heat waves can have significant impacts for poultry and other livestock.

- The potential impacts of higher temperatures, changes in precipitation patterns, and extreme weather events may make manure management more difficult for Delaware poultry and livestock farmers. For example, additional technology solutions to mitigate ammonia emissions, which increase with temperature, from animal housing may be needed. Designs for manure storage structures may need to be modified to counteract effects of extreme weather events, should such events increase in frequency and severity.

Crop Production

- Rain events of increasing frequency and intensity could have significant impacts at critical periods in crop production, such as delayed planting or post-planting washouts and increases in disease pressure.

- Rising temperatures and increased frequency of dry days may lead to crop losses, reduced yields, impaired pollination and seed development, and higher infrastructure and energy costs to meet irrigation needs.

- A longer growing season and warmer winter temperatures may result in increased competition from weed species and insect pests, and an expanding range for pests that are currently limited by winter temperatures.

- Nutrient management strategies for crop production will need to evolve to meet climate-based changes because the soil nitrogen and phosphorus cycles are very dependent upon temperature and moisture. Monitoring programs, in combination with on-farm research and extensions projects, should help identify how climate change affects nitrogen (N) and phosphorus (P) cycles and guide any necessary changes in agricultural nutrient management practices.

Chapter 7 Agriculture

Chapter Contents

- Overview of Delaware's agricultural resources
- Summary of climate change impacts that pose challenges to agriculture throughout the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to agriculture (nonclimatic impacts to resources)
- Potential impacts to agriculture in Delaware (based on current research and expert interviews – statewide scope)

7.1. Overview of Delaware's Agricultural Resources

Agriculture plays a strong role in the local and regional economies and culture throughout the state, generating close to $1.1 billion in market sales (in 2007). According to 2011 agricultural statistics, Delaware had approximately 2,500 farms and 490,000 acres in farmland (about 40 percent of the state's total acreage). The average farm size for the state is nearly 200 acres; however, more than half of Delaware's farms are less than 50 acres in size.[2]

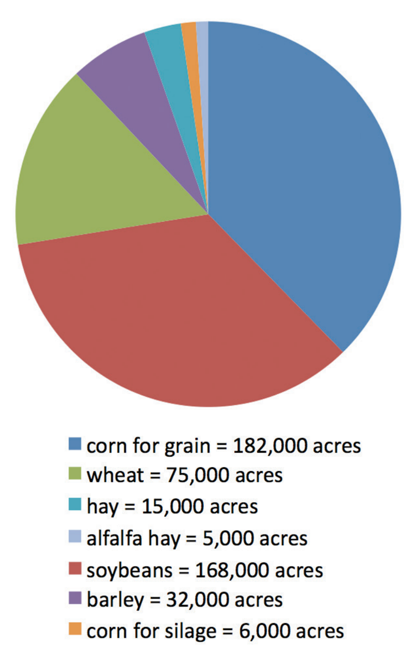

Figure 7.2. Delaware agricultural land use by crop - acres harvested (2011).
Source: Delaware Agriculture Statistics Service.

7.1.1. Agricultural Land Use

Delaware's agricultural landscape is dominated by grain crops (**Figure 7.2**) – corn, soybeans, and wheat – grown primarily as feed for the state's poultry industry, which is concentrated in the southern part of the state. Roughly half of all farm acreage is in Sussex County, while Kent County supports about one-third of all farmland. According to agricultural census data from the U.S. Department of Agriculture (USDA), in 2007:[a]

- Cropland represented 85 percent of all farmland acreage
- Irrigated land represented 24 percent of all cropland
- Acreage in corn (for grain) represented 43 percent of all cropland
- Acreage in soybeans represented 36 percent of all cropland (can include acres rotated in corn)
- Approximately 84 percent of all poultry (broiler) farms were in Sussex County
- Vegetables represented 9 percent of all cropland (for fresh market and for processing)

[a] These are the census data statistics published by the U.S. Department of Agriculture for the State of Delaware. Note that percentages and acreages may have changed. For example, irrigated acreage has increased steadily since 2007.

7.1.2. Agricultural Economy

Agriculture in Delaware makes an important contribution to the state's economy. Measured by the value in market sales, reported by the Delaware Department of Agriculture, Delaware produced nearly $1.1 billion in cash receipts in 2010. In market sales, the poultry industry and grain production dominate Delaware's agricultural market value (**Figures 7.3** and **7.4**). Sussex County ranks first in the United States for broiler production with more than 200 million birds produced each year. The state's poultry sales represent 74 percent of total agricultural sales, totaling more than $785 million in market sales in 2010. Corn and soybeans represent nearly 12 percent of total sales, amounting to more than $130 million.[3] A study conducted by the University of Delaware in 2010 estimated that Delaware's total economic contribution from all categories of agriculture is close to $8 billion, representing the added value of employment and direct and indirect expenditures. The report estimates that agriculture supports a total of 30,000 jobs, including full-time, part-time, and seasonal employment (estimate for 2008).[4]

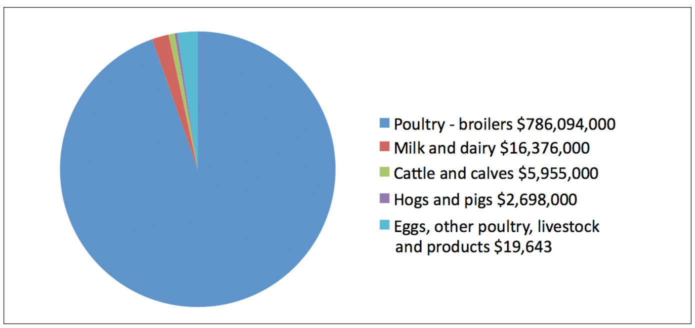

Figure 7.3. Value of poultry and livestock in Delaware (2010), measured by cash receipts.
Source: Delaware Department of Agriculture, Delaware Agricultural Statistics and Resource Directory 2010-2011.

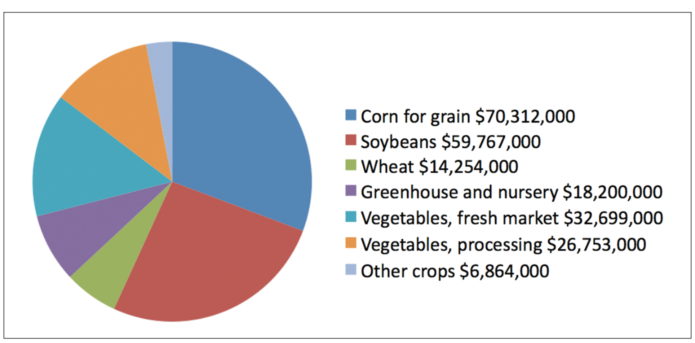

Figure 7.4. Value of crops in Delaware (2010), measured by cash receipts.
Source: Delaware Department of Agriculture, Delaware Agricultural Statistics and Resource Directory 2010-2011

Although poultry and grain crops are major contributors to Delaware's economy, there are a variety of other industries that add to the diversity and economic value of the state's agricultural sector, including:

- *Dairy*: Delaware supported 83 dairy farms with approximately 6,500 milk cows in 2007. The number of milk cows and milk production has declined in recent years, although cash receipts for milk products increased in 2010 to $16.4 million. More than half of Delaware's dairy farms are in Kent County.[5]

- *Equine*: Delaware's equine industry includes both racing and nonracing horses in three categories: private (pleasure, work, etc.), commercial (racing, breeding, boarding, etc.), and participant and spectator events (racing, shows, and competitions, etc.). A survey conducted in 2004 reported 2,000 equine operations statewide, with 13,000 equine (including racing and nonracing horses, ponies, donkeys, burros, and mules). Kent County supports the largest number of equines and operations, as well as two of the three horse racing tracks in the state. An estimated 27,000 acres of land are in equine-related use (based on the 2004 survey). The survey also estimates the equine industry output (direct and indirect) totaled more than $360 million in 2003.[6]

- *Vegetables*: Approximately 42,000 acres in Delaware were planted in vegetable crops in 2010. Vegetables for processing accounted for more than three-quarters of the total acreage, and totaled more than $19 million in value. Top crops included green lima beans, sweet corn, and green peas. Vegetables grown for fresh market accounted for one-fourth the acreage (11,400 acres) but represented a higher total value of more than $33 million (based on 2010 statistics). Fruits and vegetables grown for fresh market include sweet corn, watermelons, potatoes, snap peas, and pumpkins.[7]

- *Forestry*: Approximately 30 percent of the state supports forest land cover (371,000 acres), most of which is privately owned. The Delaware Forest Service estimates that roughly 4,800 acres are harvested annually, generating approximately $4 million of income for landowners.[8] (Note that forests and forest ecosystems are discussed further in Chapter 8, Ecosystems and Wildlife.)

- *Green Industry* (nursery, greenhouse, landscaping, sod): Delaware supports a growing industry of greenhouse and nursery crops, which produced more than $18 million in sales in 2010.[9] This includes garden bedding plants, potted plants, and cut flowers, as well as greenhouse production of vegetables, including greenhouse tomatoes. Delaware's green industry also includes a number of turf and sod farms that supply horticulture and landscape businesses in the state.

7.1.3. Agricultural Infrastructure

Agricultural operations rely on many kinds of infrastructure to produce, process, store, and transport farm products. In animal production, barns and poultry houses are critical structures for maintaining optimum conditions for animal health. In crop production, in addition to the buildings and equipment housed at the farmstead, irrigation equipment is a major investment for grain and vegetable farmers, and the operation of irrigation and pumping equipment adds maintenance requirements and energy costs. Processing facilities in Delaware include poultry, dairy, and vegetable processing plants. There are currently six poultry processing facilities in Delaware; five are located in Sussex County and one is in Kent County. Delaware is also an important producer of vegetables for processing; growers rely on canning and freezing facilities located in Delaware and neighboring states. Storage facilities for grain and other farm products are essential links for distribution and transport. These networks of infrastructure are critical for bringing Delaware agriculture products to markets throughout the country.

7.1.4. Trends in Agricultural Land Use and Production

Over the past several decades, agricultural production and the value of agricultural market sales in Delaware have increased by more than 200 percent. At the same time, the number of farms and total acreage in farmland has decreased as a result of changes in land use, population growth, and other economic factors. Statewide, the total number of farms and the total farm acreage declined by roughly 25 percent between 1978 and 2007 (**Table 7.1**). These trends in the state reflect larger patterns across U.S. agriculture: agricultural productivity has grown dramatically even as farmland acreage has declined. It should be noted, however, that development pressure and loss of agricultural land has declined in recent years due to the economic downturn, leading to less conversion of farmland to housing and other nonagricultural uses.

The decline in number of farms is also a result of consolidation of farming; as some producers leave farming, other farmers purchase their land and increase their acreage. Thus, the average farm size in Delaware has generally increased since the 1940s. Although less than 10 percent of farms are 500 acres or more in size, a small number of very large farm operations accounts for much of the agricultural production in the state.[10]

Gains in agricultural output are largely due to increased production efficiencies through technology innovations, such as traditional plant breeding and genetic engineering; new, large-scale equipment for tillage, planting, and harvesting; adoption of irrigation for grain and vegetable crops; new cropping systems (e.g., no-tillage); integrated pest management; and improvements in the efficiency of use of plant nutrients (e.g., fertilizers and manures).[11] Increasing efficiencies in livestock operations and improved animal genetics have also led to large gains in poultry production. In Delaware, the number of broilers produced increased by 69 percent between 1978 and 2007, even as the number of farms producing broilers decreased by 16 percent.

Delaware's total forest acreage has remained relatively stable in the past three decades; however,

Table 7.1 Trends in agricultural land use and production (2007).
Source: U.S. Department of Agriculture, National Agricultural Statistics Service, 2007 Census of Agriculture[12]

	1978	2007	Approx. percent change (%)
Number of farms	3,398	2,546	-25
Acreage in farmland	669,646	510,253	-24
Number of farms growing corn for grain	1,600	843	-48
Acreage in corn for grain	156,517	185,407	+18
Number of farms growing soybeans	2,124	817	-62
Acreage in soybeans	262,363	155,548	-41
Number of farms producing broilers	1,005	845	-16
Number of broilers sold	145,796,536	246,098,878	+69
Market value of livestock and poultry products	$218,310,000	$872,400,000	+300
Market value of agricultural products sold	$321,248,000	$1,083,035,000	+237

changes in forest tract size, tree age, and species composition have occurred. Forest assessments indicate that average forest tract size is declining and forest habitat is becoming more fragmented, largely as a result of development. The average size of forest ownership has declined from 30 acres in 1975 to less than 10 acres today. The Delaware Forest Service estimates that only 20 percent of all forest parcels are 500 acres or larger.[13] In addition, seedling and sapling forests represent less than 25 percent of forested land. These younger forests are needed to replace older forests as they are harvested or lost to storm damage or natural mortality. In recent decades, the species composition of Delaware's forests has been shifting from high value upland hardwoods and loblolly pine to lower quality hardwoods, such as red maple, which now comprise roughly half of the state's growing stock volume.[14]

7.2. Climate Change Impacts to Agriculture in the United States

Crop and livestock production and viability are affected by temperatures and changes in precipitation. Climate change impacts that may affect agriculture production include reduced animal and crop health and productivity related to heat stress; exposure to increased or new parasites and diseases, leading to increased mortality; and higher production costs.

7.2.1. Animal Agriculture

- Increasing temperatures may negatively affect livestock operations by increasing the intensity and frequency of summer heat stress. Heat stress can depress animal growth and reproduction for weeks or even months and result in decreased production and increased animal mortality. Agricultural operators can compensate by introduction of heat-tolerant genetics through selective breeding programs.

- Extreme weather events can damage agricultural infrastructure (barns, storage buildings, and processing facilities). Interruptions to transportation and energy can affect operations, often with costly impacts.

- Changes in temperature and precipitation may increase the impact of pathogens and parasites that affect the health of livestock. Earlier arrival of spring and warmer winters may create conditions that allow the spread of diseases and increased survival and number of reproduction cycles of insect pest parasites.[15]

Animal responses to heat are well documented in various aspects of animal production. Optimal livestock production requires temperatures that do not negatively alter the animal's functions or behaviors. When an animal's body temperature moves out of normal ranges, the animal must expend energy to conserve or reduce heat. An animal's response to heat stress is often observed as a decline in physical activity and eating or grazing activity. For example, voluntary feed intake can drop to less than half of normal amounts during hot spells.[16] As a result, the animal has less energy available for meat or milk production and/or reproduction. Continued exposure to high heat can cause death of the flock or herd.[17]

Broilers (chickens raised for meat), like many other types of livestock, are sensitive to high heat. Temperatures in the mid-90s (Fahrenheit) combined with high humidity can lead to elevated body temperatures, which result in higher feed conversion ratios, lower feed intake and weight gain, and increased mortality.[18] The timing of high heat days can also be critical; birds close to their maximum weight are more sensitive to heat stress. The majority of poultry operations exist in large indoor facilities where the birds are kept safe from adverse weather and predators, and where their health and welfare can be closely monitored. Under these conditions, heat stress can become an issue during the summer months.[19] Heat-related stresses in poultry houses are offset by ventilation systems that include fans and various types of evaporative cooling.

Dairy cows are sensitive to both heat and humidity. The optimum temperature range for milk production is between 39 and 75°F. Heat stress and decreased milk production can occur at 75°F when relative humidity is greater than 65 percent or at higher temperatures (81°F) when relative humidity is greater than 30 percent.[20] Warming temperatures could lead to increased impacts to livestock from pathogens and parasites. Earlier arrival of spring and warmer winter seasons could create conditions that allow these pests to proliferate, expanding their range both geographically and temporally.[21]

Direct damage from extreme weather, such as heavy rain or snow events, can result in huge economic costs, including repair and replacement costs of buildings and equipment, loss of income, and removal of snow, silt, or debris left behind. Severe weather events can also affect infrastructure and systems that are critical to agriculture. For example, flooding and heavy snow can slow or block transportation of crops or livestock to markets or processing facilities, or prevent deliveries of feed. Barns, grain silos, manure storage facilities, and other farm infrastructure may be affected by high winds or heavy snows, as described above in the example of poultry houses. Extreme weather can also damage or impair processing facilities for poultry and other livestock. Electricity outages caused by extreme weather events present vulnerabilities for livestock producers. There is increasing need to maintain and upgrade backup generation to cope with power disruptions.

Controlling and preventing animal diseases is a critical part of livestock operations, and is supported by extensive research, monitoring, and technical outreach programs. In Delaware, the state veterinarian is empowered with the authority to control, suppress, and eradicate infectious diseases in livestock and poultry. To assist in that effort, the University of Delaware's Poultry Health System provides surveillance and early detection of infectious diseases that can cause significant health threats to poultry. The program routinely tests for infectious diseases such as Newcastle disease, bronchitis, and avian influenza. Many vaccines developed through the nationwide university research community continue to improve poultry health and save the poultry industry millions of dollars annually.[22] There is insufficient research to determine which, if any, animal pathogens and diseases may expand in range or increase in frequency or severity as a result of climate changes. However, it is fairly well documented that if animal health suffers from other stressors (such as heat or cold stress), there is increased susceptibility to diseases that are already present in the environment.[23]

7.2.2. Crop Production

Plant production is affected by several impacts related to climate change: increased temperatures, changes in precipitation patterns and amount of rainfall, increased carbon dioxide concentrations, increased ozone levels, and changes in growing season.[24]

Temperature Impacts

- Higher temperatures, earlier arrival of spring, and increasing length of the frost-free growing season could be beneficial for some crops.

- Warmer temperatures can facilitate increased growth in crops; however, the fruit of the plant may not reach full maturity, resulting in lower yields. High temperatures during the critical reproductive stages of plant development can affect pollen viability, fertilization, and seed or fruit formation in many crops.

- Higher winter temperatures can negatively affect crops that require a chilling period for optimum flowering, fruit set, and seed development. Midwinter warming can also pose a risk for plants that emerge or bloom during an early warm period followed by a late spring cold snap or nighttime frost or freeze.

- Warmer temperatures, especially in winter, are expected to increase the northward spread of weed species that can cause significant reductions in yields through competition with crops for water and nutrients. Increasing frequency and intensity of pest outbreaks will likely boost pesticide use, resulting in economic and environmental impacts.[25]

Crops have optimum temperatures for each phase of their growth and development cycle; significant changes in seasonal temperatures due to climate change could disrupt plant growth and yields. Increases in frost-free periods may be beneficial for crops that require longer growing periods and may allow for more double and triple cropping. On the other hand, increased plant stress due to high temperatures, periods of drought, increasing weed competition, and insect and disease pressure may outweigh the benefits of an increased growing season.

Increased summer temperatures generally tend to lead to lower yields for some grain crops. For example, higher temperatures will affect pollen development and viability in corn. Pollination in corn is a critical period for development and sufficient yield. If the corn silks are exposed to temperatures greater than 95°F with low relative humidity and low soil moisture, desiccation of the exposed silks can occur, and at sustained high temperatures pollen, is no longer viable. Shorter life cycles result in smaller plants, shorter reproductive phase duration, and lower yield potential.[26] Many fruiting vegetable crops will have reduced fruit set as temperatures increase and others vegetables may flower prematurely or have reduced quality due to higher temperatures.

Increasing temperatures will likely allow the northward spread of weeds, insect pests, and diseases that already cause significant crop damage in southern states. Some aggressive weeds, such as kudzu (*Pueraria montana* var. *lobata),* which are sensitive to freezing temperatures, are limited by minimum winter temperatures.[27] Temperature is also an important limiting factor affecting the distribution of insect pests. Warmer winters are likely to increase populations of some insect pests that are currently limited in their overwintering range. Climate projections indicate the potential for expansion of the overwintering range for numerous insect species; some may be crop pests, while others may be beneficial.[28]

Changes in annual and seasonal temperatures also affect the growing season, defined as the period between the last frost date in spring and the first frost date in fall. The average length of the growing season has already been increasing: in the eastern United States, the length of the growing season has increased by approximately eight days since 1895.[29] Longer growing seasons can trigger earlier emergence of insects and promote more reproductive cycles, affecting populations of both insect pests and beneficial insect species. Milder winter temperatures and longer growing seasons may alter the life cycles of beneficial pollinator species that are critical for many flowering plant crops. A study published in 2011 reported that over the past 130 years several species of North American bees are emerging earlier in spring – by about 10 days – with most of the shift in timing occurring since 1970. The potential for "mismatch" between the timing of flowering plants and insects could occur if flowering crop species are not in sync with the earlier emergence of pollinators.[30]

Precipitation and Extreme Weather Impacts

- Increasing variability of precipitation will require farmers to cope with flood and drought conditions. Rain events of increasing frequency and intensity will have significant impacts at critical periods in crop production, such as delayed planting or post-planting washouts and increases in disease pressure.

- Increased temperatures increase transpiration in plants and cause higher water demands, resulting in the need to irrigate to mitigate water stress. This can lead to higher energy costs for pumping water and increased investments in irrigation equipment and labor. Increased water stress in plants will limit yields in crops by reducing photosynthesis.

- Extreme weather events, such as heavy rain, snow, and/or wind, can have severe impacts on crop production such as wind or rain knocking down grain crops late in the growing season and delays in planting or harvesting due to flooding of fields.

It is projected that droughts will occur during the peak growing season when crop demand for water is high. Water stress, like heat stress, can reduce plant vigor and productivity. Although irrigation infrastructure already is common throughout Delaware, increased water demand may expand the need for irrigation equipment, resulting in higher costs for capital investment and energy costs.

Plant production can be jeopardized depending on the timing and intensity of precipitation events throughout the growth cycle. For example, heavy spring rains can delay planting or force producers to operate heavy equipment on wet soils, leading to soil compaction.[31] Large rain events in the spring post-planting can cause seed washout and soil crusting, which reduce seed emergence. Field flooding during the growing season can cause crop loss due to increases in susceptibility to root diseases, anoxia (lack of oxygen in the soils), loss in topsoil, and leaching of nutrients.[32] For example, the 1993 floods of the Mississippi River in the U.S. Midwest resulted in agricultural damages estimated at $6 to $8 billion. Approximately 70 percent of total crop losses were due to saturated soils in upland areas.[33]

Carbon Dioxide and Ozone Impacts

- Increasing concentrations of carbon dioxide (CO_2) can stimulate plant growth; however, the combined effects of increased CO_2, higher temperatures, and increased ozone may collectively result in a negligible benefit to yields.

- Many weed species respond more positively than crop species to higher concentrations of CO_2. In addition, widely used herbicides such as glyphosate (trade names Roundup™, Roundup Pro™, and Accord™) lose efficacy under higher CO_2 conditions.[34]

Increasing concentration of atmospheric CO_2 has the direct effect of stimulating plant growth, although the response varies considerably among plant species and varieties. Higher CO_2 levels also trigger the partial closure of leaf pores (stomata) and thus can produce a water-conserving effect. However, when the combined effects of increased CO_2 and increased temperature are considered together, the results are mixed. Some crops, such as leafy greens, may benefit in the vegetative phase of growth, where increasing leaf area increases crop yield.[35] However, for many grain crops, the benefits of CO_2 alone are unlikely to compensate for the negative impacts of heat stress in the reproductive phase of plant development.[36]

Many weed species may benefit more than agricultural crops from combined increases in temperature and CO_2.[37] For example, research conducted on soybeans under current and increased levels of CO_2 found that while soybean growth was stimulated by higher CO_2 level, weed growth was stimulated to a greater extent, assuming normal precipitation levels.[38]

Another climate change impact related to increasing temperatures is the associated increase in ozone pollution, which is known to be damaging for many plants. Some widely grown crop species, such as soybeans and wheat, are particularly sensitive to ozone.[39]

7.2.3. Forest Management

Climate change impacts affect managed forests in ways that are complex and different than climate effects on annual crops. Forest species are long-lived, and therefore exposed to a wide range of variability in seasonal and annual weather patterns. Projected increases in temperature and atmospheric CO_2 and changes in precipitation are likely to affect forests across the United States, both directly and indirectly.

Increasing temperatures and longer growing seasons will contribute to increased forest growth. However, temperature changes will affect different tree species to varying degrees and are likely to alter species composition in forests. Some tree species may benefit by expanding their range and/or increasing population, while other species may decline or shift to higher elevations or higher latitudes. In the northeastern United States, for example, some forest types, such as oak-hickory, are expected to expand, while maple-beech-birch forests are expected to contract.[40] Increasing temperatures may also lead to greater mineralization of soil nutrients, which can enhance forest growth but may also lead to increased nutrient losses to streams and rivers.[41]

Rising levels of atmospheric CO_2 are likely to increase forest productivity and may also increase carbon uptake and storage. Research conducted through Free Air CO_2 Enrichment (FACE) experiments suggests that North American forests will absorb and retain more CO_2 – increasing the rate of carbon sequestration – where there are nutrient-rich soils with no water limitations.[42]

Changes in precipitation will affect different tree species in different ways. Overall increases in precipitation may benefit some species. However, projected changes in precipitation patterns for the eastern United States suggest an increase in heavy rain events that may lead to increased flooding, erosion, and loss of sediment into streams – all of which may have negative consequences for forest management.[43] Climate change impacts may also affect forests indirectly, through increases in outbreaks of forest insects and pathogens. Increasing temperatures can affect insect populations by increasing overwintering survival and life cycle development rates as a result of warmer winter temperatures and a longer growing season. Insect pests may also shift or expand their ranges as temperatures rise.

7.3. External Stressors

Climate change is one of many stressors that can affect agricultural productivity and profitability. Other external stressors include land use changes, environmental regulations, energy and input costs, and fluctuations in market demands and prices. Some of these factors are local or statewide – such as land use changes and population growth. Others are national or global – such as global market prices for commodities.

Land use changes in Delaware's rural landscape have followed a pattern similar to much of the United States. As described above, the number of farms and total acreage in farmland in Delaware has declined by approximately 25 percent over the past 30 years. Loss of farm acreage is driven in part by population growth and increasing demand for new urban, suburban, and commercial development. This growth spurred rising land values that have added pressure to convert farmland to other uses.

Farmland that lies in close proximity to existing towns and cities may be subject to annexation and subsequent changes in zoning that allow for subdivision in lot sizes that support residential development. Between 2004 and 2008, incorporated towns and cities in Delaware expanded their boundaries by 9,735 acres; more than half of this newly incorporated land (5,396 acres) was in Sussex County, which is dominated by agricultural land use. Another trend in housing growth that affects the agricultural landscape is a growing demand for homes in unincorporated areas outside towns and urban centers. In addition, between 1995 and 2000, approximately 23 percent of new construction was on lots of one acre or more in size.[44] It should be noted, however, that the pace of development – and subsequent pressure on agricultural land – varies over time in response to economic cycles. The recent downturn in the economy, both nationally and statewide, has slowed the pace of building and land conversion over the past five years.

Environmental regulations and government programs can present constraints and additional costs to farmers, but can also provide some financial support and incentives for adopting agricultural practices that reduce environmental impacts and improve agricultural productivity. Federal and state water quality and air quality regulations affect most growers and producers. Delaware's Nutrient Management Law requires a nutrient management plan to be developed for the majority of operations with the goal of reducing the loss of nitrogen and phosphorus from agricultural lands by better management of all nutrient sources (fertilizers, manures), including their methods, rates, and timing of application. Additionally, the law requires certification of anyone who generates or handles nutrients as well as those individuals who write the plans. The federal Clean Water Act through the National Pollution Discharge Elimination System Permitting Program also requires concentrated animal feeding operations (CAFOs) to obtain a permit limiting the pollution that can be discharged from these sites.

Although compliance with environmental regulations can be costly, voluntary programs offer some opportunities to help farmers implement management practices designed to reduce losses of nutrients and sediments to water and/or air. Federal programs through the USDA and local conservation districts provide financial assistance through cost-share grants to install water quality improvements such as buffer strips and drainage structures. In addition, federal Farm Bill programs cover a wide range of economic incentives for farmers in the form of loans, price supports, and crop insurance.

Energy costs represent a significant expense in agricultural production, and include both the direct costs of fuel and electricity and energy-intensive inputs, such as fertilizer. Energy expenses averaged 13 percent of total production costs in the United States in the period 2005 to 2008 (roughly half of this amount for direct energy use and half for fertilizer). However, some major field crops such as corn require much higher energy inputs. For irrigated crops, energy demands are greater, but may be offset by the value of increased yield. Energy-related costs affect livestock producers also, particularly when feed costs increase as a result of higher energy prices relative to total production costs. Poultry production is somewhat less affected than other types of meat production (poultry requires less feed per pound of meat produced); however, poultry growers also must cope with increased energy costs in heating and cooling of poultry houses, and poultry processing can also be affected by higher energy costs.[45]

Projecting future impacts of energy costs on agriculture is difficult, given the complexities of fluctuating energy prices and the uncertain effects of future governmental policies on carbon-based fuels. However, numerous government programs and incentives have developed in recent decades to assist farmers in improving energy efficiency and adopting renewable energy sources. In addition, there may be a future potential for agricultural producers to participate in emerging carbon markets by using practices that reduce greenhouse gas emissions, creating marketable offset credits.

Fluctuating market prices are a significant external stressor in Delaware agriculture. For some agricultural products, such as fruit and vegetables, prices may be determined largely by local and regional markets. For commodity crops, such as corn and soybeans, national and global market demand and supply are key drivers in crop prices.[46]

Livestock production also follows trends in market supply and demand. Delaware's poultry industry produced a record 282 million broilers in 2005; the number has declined in recent years to a total of 217 million in 2011, due in part to oversupply and low prices. Higher prices for feed corn have also had an impact in Delaware; two poultry companies filed for bankruptcy in 2010 and 2011, both citing the impact of increasing cost of feed.

Delaware's three largest agricultural products – poultry, corn, and soybeans – are highly interdependent. The feed grain crops grown in the Delmarva region supply roughly two-thirds of the feed grain needed for the broiler industry; the remaining third must be imported, generally from the Midwest grain belt. The proportion of locally grown feed grain varies from year to year, and may be increasing as a result of the expansion of irrigation, which can greatly increase crop yields. Any significant changes to the availability and prices of grain crops – locally, nationally, and globally – have direct impacts on poultry growers' costs and profitability.

7.4. Potential Impacts of Climate Change to Delaware's Agriculture

7.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under the higher as compared to the lower scenario and by end of century as compared to more near-term projections. The **lower scenario** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of CO_2 and other greenhouse gases. The **higher scenario** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

- The growing season is also projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost (**Figure 7.1**).

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

Precipitation Changes

- Average precipitation is projected to increase by an estimated 10 percent by end of century, consistent with projected increases in mid-latitude precipitation in general.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

7.4.2. Vulnerability to impacts

Agriculture is a highly dynamic industry. Like all businesses, agricultural producers cope with a range of variables and risks, including market demand, economic conditions, regulatory requirements, and labor and input costs. In addition, agriculture is especially vulnerable to weather-related risks. Seasonal and annual weather fluctuations and climate-related events have a strong influence on yields in both crop and livestock production. As a result, there is considerable variability in year-to-year agricultural output. Farmers have managed to cope with these dynamic conditions since the beginnings of agriculture, and therefore have considerable skill and experience in adapting to change.

Climate change represents a potentially increasing exposure to variability, a "risk magnifier" that may affect the limits within which certain types of agriculture activities are economically viable. This section discusses potential vulnerabilities in Delaware's agricultural sector by examining several types of agricultural production that could face increasing challenges from rising temperatures, changes in precipitation, sea level rise, and exposure to extreme weather events. Also noted are some practices already being developed that may provide adaptive strategies for climate change, and current and ongoing research underway to better understand the potential impacts of climate change on agriculture.

In a changing climate, warming temperatures may offer benefits or opportunities as well as challenges. As previously described, the United States has seen overall increases in agricultural production in recent decades, through the development of new varieties of crops and increasing efficiency in agricultural operations. Some crops have benefitted from changes in climate and weather patterns. However, in regard to extreme weather, there is very little potential for benefits to agriculture or to any other sector. In recent decades, the frequency, intensity, and duration of extreme weather events have had significant, largely negative, economic impacts on crop and

Increasing Irrigation Use and Efficiency

In Delaware, irrigation is used for the main grain crops – corn, soybeans, and wheat – as well as for most vegetable crops. Irrigated crop acreage has more than tripled in Delaware in the past several decades. Irrigated acreage now accounts for roughly one-fourth of all crop acres, and continues to expand. Increasing efficiency in irrigation benefits farmers by ensuring that crops get sufficient water when they need it, based on weather and soil moisture conditions. Improving irrigation efficiency also reduces water waste, which helps lower costs. A number of programs and research projects in Delaware currently focus on increasing irrigation use and efficiency:

The Delaware Rural Irrigation Program (DRIP) is a joint effort of the Delaware Department of Agriculture and Delaware Economic Development Office. The program, created in 2011, offers no-interest loans to finance up to 25 percent of the total cost of installing irrigation systems. In the first year, the program has helped bring more than 850 acres of farmland under irrigation.

The Delaware Irrigation Management System (DIMS), launched in 2012 by the University of Delaware, is an irrigation scheduling application developed specifically for Delaware that uses automatically updated weather data. The online system is designed for a number of grain and vegetable crops, including corn, soybeans, sweet corn, cucumbers, watermelons, cantaloupes, lima beans, and peas.

University of Delaware Cooperative Extension is also conducting field research on subsurface drip irrigation (SDI), a system of plastic irrigation tapes or drip lines placed 10 to 16 inches below ground to provide water at the plant's root zone. SDI is well suited to small or irregularly-shaped fields that are impractical for center-pivot irrigation. SDI is currently being tested with corn, soybeans, lima beans, and small grains in a variety of irrigation scenarios to determine which scenario results in the best yields and improves nutrient uptake and water efficiency.

Improvements in technology can help increase irrigation efficiency, but optimizing that efficiency depends on having the best available data on conditions in the field. For example, when data from soil moisture sensors located throughout a crop field are used in conjunction with irrigation scheduling software, there is greater accuracy in determining the timing and amount of irrigation needed. Proper calibration of irrigation equipment is also important for ensuring that crops are receiving the intended amount of water. To date, much of the irrigation research has been done on heavy soils in low humidity regions. There is a need to refine and regionalize irrigation research to determine the ideal irrigation management strategies for Delaware's sandy soils and humid climate.

livestock production. Agriculture in the United States and globally has seen dramatic losses and economic impacts due to extreme temperatures (high heat or cold periods), changes in rainfall (drought or flooding), and seasonal changes (early spring or late frost).

7.4.3. Animal Agriculture – Heat Impacts

Heat stress resulting from extreme heat days or sustained heat waves can have significant impacts for poultry and other livestock. Hotter summers lead to greater heat-related stresses on animal health and reduced feed and growth efficiency. Heat, drought, and extreme weather may affect the dairy industry by reducing forage supply and quality. (Forage generally refers to the plants eaten by grazing animals in pasture, and may include hay or silage harvested and later used as feed.) Forage accounts for more than half of the feed requirements for dairy cows, and cannot be readily purchased to make up short supplies. Extreme heat also causes poor reproduction in dairy cows. Under higher emission scenarios, by mid-century dairy cattle in Delaware would be under moderate heat stress levels that could result in a 10 to 25 percent decrease in milk production.[47]

The broiler industry has an advantage in coping with heat events because the animals are raised indoors in poultry houses that are environmentally controlled. Since the 1990s, the construction of poultry houses in Delaware has changed; the open, curtain-style houses have largely been replaced by enclosed poultry houses with insulation and ventilation systems to help maintain the necessary range in temperature, humidity, and air quality within the houses year-round.

Higher summer temperatures will require greater ventilation and thus increase energy usage. Improvements in tunnel ventilation poultry houses have also increased capital investment costs for growers. Many farms have upgraded electrical equipment and well capacity to meet the increasing demand for water from evaporative cooling. One of the most cost-effective measures used to cope with temperature extremes (both heat and cold) is weatherization of barns, poultry houses, and other livestock structures. Just as with any house or commercial building, effective insulation and ventilation of livestock structures can improve animal health by reducing cold or heat stress, and improve energy efficiency, reducing costs of heating and cooling.

Genetic improvements in poultry breeds are a long-term strategy for coping with increasing temperatures. Research is currently underway at the University of Delaware to study the effects of heat stress in poultry by comparing modern breeds to poultry breeds of the 1950s. As part of a 5-year study funded by USDA, UD professor Carl Schmidt is looking for genetic variations that have been bred out of modern chickens, affecting their resistance to heat stress.

Managing Heat Stress in Poultry

"Tunnel ventilation" houses include fans with evaporative cooling units to provide air cooling. Ventilation systems are designed to improve indoor air quality in winter as well as summer. Keeping poultry at a comfortable temperature supports overall health, growth, and weight gain in broilers, and helps improve their resistance to disease. Providing a climate-controlled environment also allows growers to produce more pounds of broilers at commercial densities.

The advantage of technology comes with two costs: system maintenance and energy costs. Achieving the optimum advantage of technology requires that the systems be carefully maintained and monitored; ineffective or failing equipment can result in rapid change in heat and humidity, leading to severe heat stress. Energy to operate fans and other equipment is generally provided from grid sources, but back-up generators are essential equipment that must be properly maintained. Improvements in building insulation and ventilation can improve energy efficiency and thus reduce energy costs. Energy audits are available to poultry growers and may be required for certain federal cost-share programs that support energy efficiency improvements in poultry operations.

7.4.4. Crop Production – Heat and Changing Rainfall

Changes in temperature and/or precipitations patterns may alter the viability of some crops in the state and promote the need for alternative farming and agricultural practices. Delaware may see positive and negative impacts on crop productivity. Continued increases in average temperatures and temperature extremes may produce a negative impact for some crops when temperatures reach a critical threshold. Crops are also sensitive to extreme fluctuations in precipitation, both in amount and timing of rainfall at critical points of plant development.

Grain farmers in Delaware, as in other parts of the country, have coped with heat waves and drought cycles for decades. The large acreages of sandy soils with low moisture-holding capacities are a major contributing factor to Delaware's drought-related crop production problems. Two important strategies have enabled farmers to adapt to changing conditions. First, genetic researchers continue to develop new varieties and hybrids of crop species that are adapted to common environmental stressors, including drought tolerance. Second, investment in irrigation equipment and improvements in irrigation efficiency have dramatically increased yields of many crops and buffered the uncertainties of seasonal rainfall patterns. The benefits of irrigation for crop farmers in Delaware are significant. Although crop yields per acre vary within the state, water is the single most important factor in determining yield. Irrigation increases overall productivity and provides an important buffer during prolonged or recurring drought periods. Irrigation also provides improvement in nutrient efficiency in dry conditions: during drought periods, irrigated crops are potentially twice as efficient at nitrogen recovery as nonirrigated crops.[48]

High heat also damages vegetable and fruit crops. At temperatures above 94˚F, photosynthesis decreases and can lead to reduced plant growth and lower yields. High nighttime temperatures are especially damaging, as plant respiration increases and limits fruit and seed development. Inadequate water and dry soil add to heat stress; hot dry wind is a significant factor in heat buildup in plants and accelerates damage to crops. Plant tissues die at temperatures of around 115˚F, indicated by scorched leaves and stems and sunburned fruits.[49] High temperatures can also aggravate blossom end rot, a condition that affects tomatoes and peppers, by interfering with calcium movement through the plant. In hot weather, transpiration increases through the leaves, reducing the amount of calcium received by the fruits.[50] In summary, the major vegetable crops grown in Delaware (lima beans, sweet corn, peas, cucumbers, and snap beans) will be at risk for having limited yields due to heat and water stress. Some of this can be mitigated with plant breeding efforts and cultural practices, such as better irrigation.[51]

Increased levels of ozone are another factor associated with high temperatures that can cause serious damage to vegetable crops. Ozone is a strong oxidant formed by the combination of sunlight and volatile organic compounds, generally from emissions from fuel combustion; crop damage is often most visible in fields closest to major roadways. Crops in Delaware susceptible to ozone damage include watermelons, cantaloupes, snap beans, pumpkins, squash, and potatoes. Ozone damage in sensitive vegetable crops develops when ozone levels are 70 to 80 parts per billion (ppb), which is roughly equivalent to the 8-hour ozone standard under air quality regulations.[51]

7.4.5 Weeds, Diseases, and Insect Pests

There is very little research in Delaware to confirm that climate change impacts will cause or accelerate the spread or incidence of weed species, insect pests, or plant pathogens. Weeds and pests may be increasing in response to climate changes as well as to other variables. For example, weeds that are drought-tolerant may expand rapidly in dry years, while fungal diseases may spread in wet years. Crop species that are already stressed by extreme temperature or precipitation conditions (e.g., high heat, wet soils) may be more affected by these pests and pathogens.

Some weed species and insect pests are likely to expand their range northward as climate warms. Species that now flourish in the south may move into areas in the Delmarva Peninsula that were previously too cold to support their populations. In addition, ecological disturbance caused by extreme weather events could facilitate the spread of invasive species, as nonnative species encroach into disturbed ecosystems more quickly than native species can re-establish. The following discussion provides a few examples of weeds, diseases, and insect pests that represent known and potential threats to Delaware agriculture and forests. (Note these are described here only to provide a sample of potential impacts, not as a comprehensive summary.)

Palmer amaranth (*Amaranthus palmeri*) is a plant species native to the southwestern United States and is a problem weed in crop fields throughout the South. Related to pigweed, Palmer amaranth has been described as "pigweed on steroids" because of its rapid and aggressive growth. Without effective control, the plant can reach 5 to 6 feet in height and overwhelm a crop field within a few years. Because of its ability to grow quickly, effective control requires herbicide treatment within just a few days after the plant emerges, before the plant reaches 4 inches in height.

As a further challenge to controlling this aggressive weed, a variety of Palmer amaranth that is resistant to the herbicide glyphosate (Roundup™) is known to occur in Georgia and North and South Carolina. In addition, some Palmer amaranth biotypes are resistant to multiple herbicide modes of action. Delaware observations of Palmer amaranth were first noted in the September 2010 posting of the Weekly Crop Update by the University of Delaware Cooperative Extension, but early indications were that this was not the herbicide-resistant variety of the plant, and therefore it could be controlled with glyphosate. However, in June 2012, the presence of glyphosate-resistant Palmer amaranth was confirmed on the Delmarva Peninsula. The Weekly Crop Update notes that in southern states where glyphosate-resistant Palmer amaranth has appeared in cotton fields, some farmers have had to resort to hand weeding to control this weed species.[52]

Soybean rust (*Phakopsora pachyrhizi)* is a fungal disease that causes significant damage to soybean crops and can result in losses of up to 90 percent. The fungus is spread by windblown spores, and thus has the potential for long-distance dispersal. It is thought that soybean rust became established in the continental United States as a result of wind-borne spores carried by Hurricane Ivan in 2004.[53] Soybean rust fungus is an obligate pathogen that cannot spread without a living plant host. Soybeans are one of many plant species that are known hosts, including other bean species, clover species, and kudzu (*Pueraria montana* var. *lobata).* Because it requires a living host to survive, soybean rust fungus overwinters only in frost-free regions.

Epidemics of the disease can occur where the fungus survives the winter and environmental conditions are warm and wet. Infection begins when viable spores land on the leaves of a host plant species. Leaves must be wet, and temperatures must be in the range of 54°F to 84°F. The USDA and state agricultural programs have been carefully monitoring soybean rust and tracking changes in its distribution each year. In 2013, soybean rust fungus was found in eight states (Alabama, Mississippi, Florida, Georgia, Louisiana, South Carolina, Arkansas, and North Carolina). Soybean rust has not yet been found in Delaware, and has not been detected in neighboring states. The University of Delaware Cooperative Extension forecasts that the disease does not pose an immediate threat to soybean growers in the state.[54]

Southern pine beetle (*Dendroctonus frontalis)* is a native insect pest found throughout the southern and southeastern United States that can infect and kill many species of pine within its distribution. In Delaware, and in much of the southeastern United States, the primary host is the native loblolly pine (*Pinus taeda*). In New Jersey, more than 20,000 acres of pitch pine (*Pinus rigida*) forest have been infected in recent years. Since the mid-1990s, Delaware scientists have participated in a regional study to monitor the southern pine beetle by surveying four sites in loblolly pine and one pitch

Salt-Tolerant Crops

The Delaware Sea Grant program has been conducting field research on seashore mallow *(Kosteletzkya virginica)*, a salt-tolerant marsh plant, to evaluate its potential as an oil and feed crop. The plant produces seeds with an oil content of 18 to 20 percent – similar to soybeans – and has a fatty acid profile similar to cottonseed oil. In addition, seashore mallow can be planted and harvested with conventional farm machinery.

As a native plant adapted to brackish and saline conditions, seashore mallow can survive and even thrive in coastal areas where soils have been affected by high spring tides or storm tides that flood low-lying farmlands. The plant is also suitable for crop fields where groundwater sources for irrigation have become too brackish or saline for other crops. As a marsh plant, seashore mallow is flood-tolerant; as a perennial plant with a deep root system, it is also drought-tolerant.

The development of seashore mallow as a commercially viable crop may offer farmers a transition option for agricultural fields that are exposed to saltwater from storms and from sea level rise. Coastal fields planted in seashore mallow could supply ecosystem benefits by providing a buffer to reduce erosion and nutrient runoff on land that would otherwise be left fallow.

pine stand in Sussex County. The southern pine beetle uses a "mass attack" strategy in which large aggregations of beetles respond to pheromones emitted by female beetles. The mass infestation of beetles overwhelms the trees' natural defense system of resin production. In southern states, the emergence of overwintering beetles coincides with the blooming of flowering dogwood (*Cornus florida* L.). The initial phase of dispersal is followed by rapid and widespread infestations. Increasing temperatures are likely to affect the range of this insect species; a future northward range expansion is projected for several southern insect pests, including the southern pine beetle.[55] In addition, a longer growing season may allow for a greater number of reproductive cycles. In Delaware, the southern pine beetle typically has two to three generations per year;[56] however, the species can produce as many as seven generations per year as its reproductive cycle accelerates in the spring and summer.[57] Current management of this insect pest includes active monitoring and fast response to outbreaks to prevent widespread mortality from the southern pine beetle.

7.4.6. Agricultural Land Use – Sea Level Rise

A relatively small percentage of agricultural land in Delaware is located in coastal regions that may be affected by sea level rise. The Sea Level Rise Vulnerability Assessment for Delaware assessed agricultural lands identified as Prime Farmland and Farmland of Statewide Importance and found that only 2 to 4 percent of these highly productive soils are potentially exposed to sea level rise under the three scenarios (1.6-, 3.3-, and 4.9-foot rise by 2100). Although the percentage of the total statewide acreage is small, the number of acres of potentially inundated farmland does have an impact on local agricultural communities. The Sea Level Rise Vulnerability Assessment estimates a range of 12,564 to 32,361 acres (1.6-foot and 4.9-foot rise, respectively) could be inundated. In addition to the farmland directly affected by inundation, another potential impact to coastal agriculture is the risk of salt water intrusion into groundwater used for irrigation or into shallow aquifers. Increasing salinity in water applied or available to crops will affect crop yields and the productivity of soils even before inundation occurs.

7.4.7. Nutrient Management – Climate Impacts

Climate change impacts may have direct and indirect effects on nutrient (nitrogen and phosphorus) and sediment losses from agricultural systems. Nutrient management is a critical component of farm management, for both animal agriculture and crop production. Nutrient losses have negative consequences for farmers because they represent economic losses (applied nutrients are an input cost), and because of the environmental impacts of nutrient leaching and runoff into waterways and emissions from

Table 7.2 Climate change impacts and nutrient management

Climate Change Stressor	*Potential Vulnerability*
Increasing temperatures	• Increased volatilization losses of ammonia-N, a nutrient associated with animal production, are known to occur as temperature increases; animal facilities may require new technology solutions to prevent air quality impacts from ammonia release. • Increased volatilization of surface-applied ammonia-based fertilizers or poultry manures, both commonly used for crops in Delaware, occurs as temperatures increase. This can reduce N use efficiency (economic cost) and may be a potential air quality impact; wider use of practices such as soil incorporation of manures and fertilizers to mitigate ammonia volatilization losses may be required. • Manure organic N will be converted to nitrate-N more quickly and completely in warmer soils, assuming adequate soil moisture. Thus, practices to prevent nitrate leaching from Delaware's sandy soils will likely need to be more efficient.
Changing precipitation patterns - drought	• Drought conditions reduce the efficiency of plants in using applied nitrogen fertilizers and manures, leading to lower yields and increased concentrations of nitrate-N in soils at the end of the growing season that can be susceptible to leaching losses during late fall and winter. • Lower yields also lead to a slower drawdown of phosphorus in "high P" soils via crop harvest; these conditions may lead to a need to further expand or increase the efficiency of irrigation use in Delaware cropping systems to counteract any increases that may occur during drought.
Changing precipitation patterns – extreme rain events	• Prolonged and intense periods of precipitation will increase runoff of sediment and nutrients to surface waters. • Extreme rain events increase the risk of nutrient losses from overflow of manure storage facilities. • Application of organic nutrient sources may be delayed or made more difficult in wet conditions following extreme rain events, and may lead to increased nutrient losses.
Extreme weather events	• Structures related to best management practices may fail or be damaged, resulting in losses of nutrients and sediment; this can include buffer strips, drainage structures, constructed wetlands, and manure storage facilities.

croplands of greenhouse gases. Nutrient losses can also deplete soil fertility and thus reduce crop productivity. The potential impacts of higher temperatures, changes in precipitation patterns, and extreme weather events will present a different set of nutrient management challenges for many Delaware farmers. However, changing climate conditions may offer some beneficial trade-offs. For example, longer growing seasons will lead to greater growth of winter cover crops, making them more effective in using nutrients remaining in soils after crop harvest. **Table 7.2** summarizes some potential vulnerabilities that climate change impacts may present for nutrient management.

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Chapter 8 – Ecosystems & Wildlife – Summary

Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

- The growing season is also projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3-4 days per year under higher scenarios by 2080-2099 (**Figure 8.1**).

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

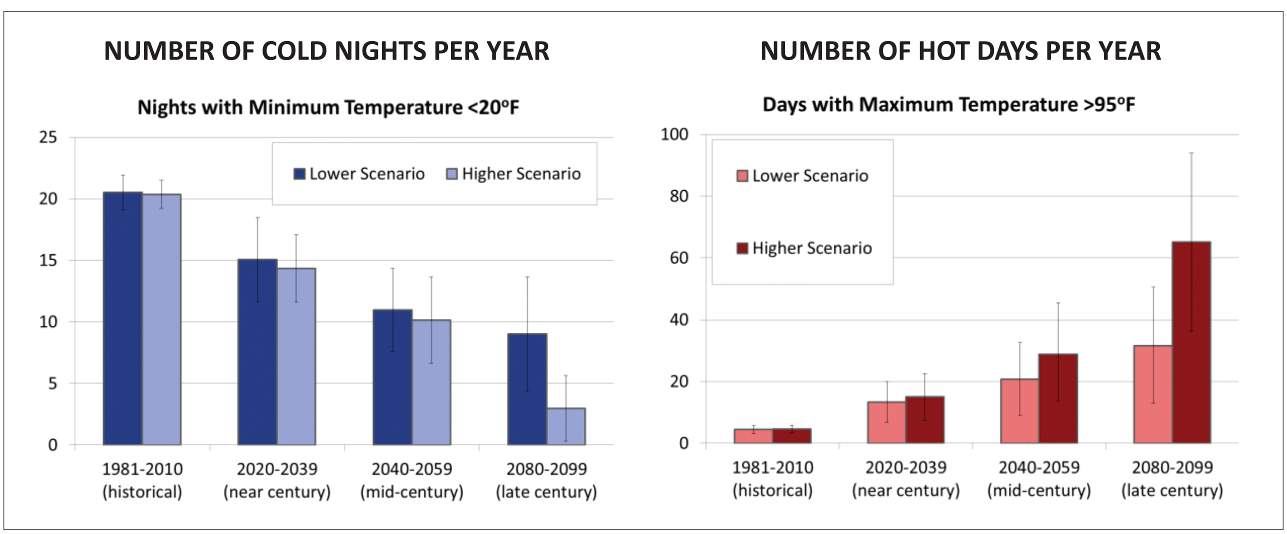

Figure 8.1. Projections for temperature extremes indicate an increasing number of very hot days and decreasing number of very cold days and nights. Differences between the high scenario and low scenario are greater by mid-century and end of century. Source: Hayhoe et al. (2013).

Precipitation Changes

- Precipitation is projected to increase, particularly in winter (**Figure 8.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 8.2**).

Potential Impacts to Ecosystems and Wildlife

- Many of Delaware's ***wildlife species*** will face changes in habitat quality, timing and availability of food sources, abundance of pests and diseases, and other stressors related to changes in temperature and precipitation. Species with very restricted ranges and isolated populations are likely to be most vulnerable to climate change impacts, compounded by other stressors. Changes in temperature and precipitation will affect species that depend on wetland and aquatic habitats.

- Delaware's ***beach and dune ecosystems***, including beaches, dunes, dune swale wetlands, and tidal flats, are already vulnerable to coastal storms. If sediment input into the system is unbalanced, the combined effects of sea level rise and severe storms may lead to increased erosion and loss of beaches and dunes. Barrier beaches and dunes may be subject to more frequent overwash from storm surge, and may be increasingly vulnerable to breaching and formation of new inlets.

- Delaware's diverse range of ***wetland and aquatic ecosystems***, including tidal, nontidal, freshwater, brackish, and saltwater wetland habitats, as well as stream and riverine habitats, will be vulnerable to sea level rise and increased storm surge from extreme weather events. Climate change impacts will likely accelerate erosion in tidal marshes, leading to further wetland losses, landward migration of marsh habitat, or conversion to open water. Increased temperatures and more frequent droughts will stress freshwater habitats, including streams, rivers, and ponds. Higher water temperatures are likely to increase the incidence of harmful algal blooms.

- Delaware's ***forest ecosystems*** may experience shifts in the range of forest species and composition of forest communities, triggered by changes in temperature. Increased frequency and/or duration of drought combined with increased air temperatures will lead to higher evapotranspiration and decreased soil moisture. These factors are likely to contribute to plant stress, resulting in decreased productivity and greater susceptibility to pests and diseases.

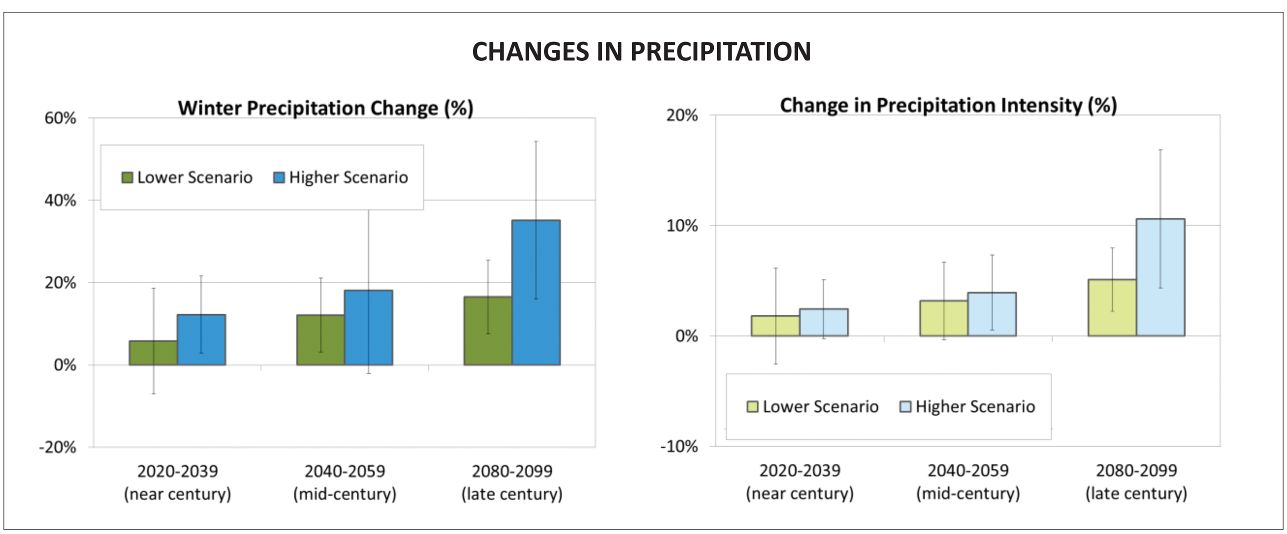

Figure 8.2. Precipitation increases are projected, primarily for winter and fall. Increasing precipitation intensity reflects projected increases in the frequency of heavy rainfall. Source: Hayhoe et al. (2013).

Chapter 8

Ecosystems and Wildlife

Chapter Contents

- Overview of Delaware's ecosystem and wildlife resources
- Summary of climate change impacts that pose challenges to ecosystems and wildlife in the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to ecosystems and wildlife (nonclimatic impacts to resources)
- Potential vulnerabilities to ecosystems and wildlife in Delaware (based on current research and expert interviews – statewide scope)

This chapter includes an overview of the state's wildlife species and ecosystems. The overview section (8.1) provides a very brief summary of wildlife species; a detailed description of all of Delaware's fish, wildlife and plant species, including species in the marine environment, is beyond the scope of this Assessment. The overview section also summarizes Delaware's rich diversity of habitats into three general ecosystem types: beach and dune, wetland and aquatic, and forest. Climate change impacts are not limited to habitats found in these ecosystems, but not all ecosystems and habitat types could be fully described in the overview section. The Delaware Division of Fish and Wildlife is the primary source for more information on the statewide distribution and status of fish, wildlife, plants, and habitats.

This chapter also includes a brief discussion of the functions that ecosystems serve, not only for the species and habitats they support, but for physical and biological functions on which human societies depend. Ecosystem goods and services are generally described as the "benefits people obtain from ecosystems." This definition is reflected in the Millennium Ecosystem Assessment[2] and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[3] Ecosystem services include:

- *Provisioning services* that provide ecosystem goods such as food, freshwater, timber, fiber, and fuel;
- *Regulating services* that moderate climate, floods, disease, wastes, and water quality;
- *Supporting services* that provide essential functions that maintain and support life on earth, such as soil formation, photosynthesis, and nutrient cycling; and
- *Cultural services* that support human well-being through recreational, aesthetic, and spiritual benefits.

Ecosystem services are also discussed in other chapters of the Climate Change Impact Assessment. For example, the Agriculture chapter (7) reflects the provisioning services in agricultural systems. Ecological services are also discussed in Chapter 9, Infrastructure, to underscore the importance of natural systems in providing benefits that support human needs.

8.1 Overview of Delaware's Ecosystems and Wildlife

Delaware's diversity of wildlife and habitats reflects its unique geography. Bordering both the Delaware Bay and the Atlantic Ocean, the state supports extensive coastal and estuarine habitats. The state's terrestrial habitats fall within the Coastal Plain and Piedmont physiographic regions (**Figure 8.3**). These are areas defined by distinct geology, topography, and communities of native plants and animals. The major drainage basins and watersheds

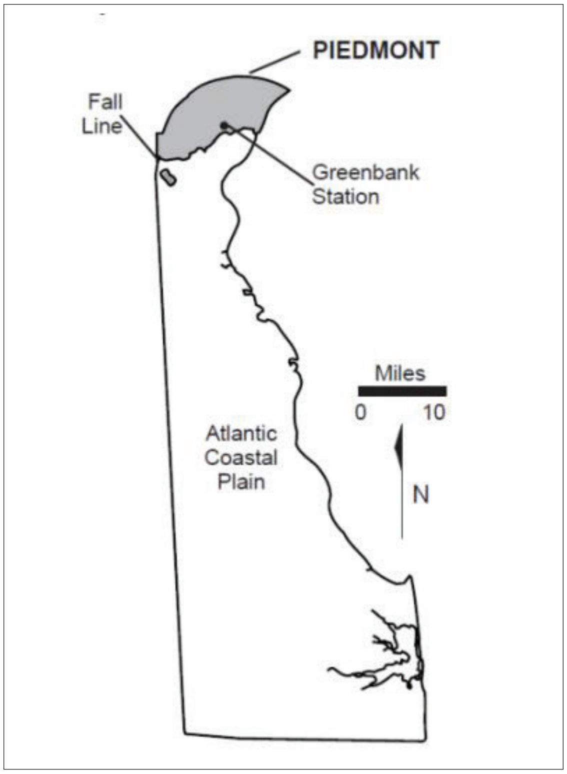

Figure 8.3. Delaware physiographic regions. Source: Delaware Geologic Survey.

also help guide discussions about the distribution of habitats and species throughout the state. Delaware has four major basins and 45 watersheds.

Ecosystem types can be described or categorized in different ways. Some classification systems describe geophysical characteristics, while others describe the dominant vegetation types or vegetation communities (assemblages of plant species that occur together). The following summary draws from the descriptions of key wildlife habitats in the Delaware Wildlife Action Plan, 2007-2017.[4] The plan identifies more than 125 types of habitat, more than 50 of which are considered habitats of conservation concern.[a]

For this Assessment, Delaware's habitat types are described briefly within three general ecosystem types:

- **Beach and dune ecosystems** include habitats found in the zone extending from the landward limit of the dunes to the sand or mud intertidal flats exposed at low tide. Low wetland swale habitats found among the dunes are also included in this ecosystem. Beach and dune habitats are found along the Delaware Bay and Atlantic Ocean shoreline.

- **Wetland and aquatic ecosystems** include wetland and aquatic habitats that are tidal, nontidal, freshwater, brackish, and saltwater. Examples of wetland habitats found in Delaware include coastal wetland impoundments, vernal pools, Coastal Plain seasonal pond wetlands, peat wetlands, and Piedmont stream valley wetlands. Examples of aquatic habitats include ponds, reservoirs, streams, rivers, bays, and oceans, including the open waters of these habitats and submerged bottom substrates, submerged aquatic vegetation, and exposed riverine sand and gravel bars and shorelines. Wetland and aquatic habitats are found extensively throughout the state in all major watershed basins in Delaware: Delaware Bay and Estuary, Chesapeake Basin, Delaware Inland Bays, and Piedmont Basin.

- **Forest ecosystems** include Piedmont upland forest, Coastal Plain upland forest, forested floodplain and riparian swamps, isolated forested wetlands, and freshwater tidal forested wetlands. Young forest habitat consisting largely of seedlings and saplings is also addressed; however, other early successional habitats such as shrub or grass and other herb-dominated field habitats and edge habitats (transition zones between forests and fields or marsh) are not addressed in this Assessment. Forest habitats can be found throughout the state.

8.1.1. Wildlife Species

More than 3,200 species and varieties of plants and animals have been documented in Delaware, including more than 1,000 species of animals[b] and more than 2,200 species and varieties of plants.[c] More than 450 animal species are identified

[a] Habitats of conservation concern are habitats that are rare, have special significance in Delaware, are particularly sensitive to disturbance, and/or have a high diversity of rare plants.

[b] This total includes invertebrates and native and nonnative species.

[c] This total includes native and nonnative species.

as "species of greatest conservation need" in the Delaware Wildlife Action Plan,[5] which was developed to address the need to manage for a diversity of habitat types, with the goal of "keeping common species common" while continuing to protect rare animal species. Plants are not addressed in the Delaware Wildlife Action Plan; however, the Delaware Division of Fish and Wildlife maintains the official list of plants occurring in the state, including distribution and status information for each species. Of 1,586 species and varieties of native plants documented in Delaware, 573 (36 percent) are rare or uncommon.

Historically, rare or endangered nongame species have been monitored and managed separately from game species. This focus has shifted to a more integrated approach to wildlife management that emphasizes the importance of the habitats on which both game and nongame species depend. Nonetheless, because there will be a specific interest from hunters and anglers on the impacts of climate change to species harvested for recreational and commercial purposes, some of these species are specifically noted here.

The Delaware Division of Fish and Wildlife manages 58 species classified as game animals, including 44 bird species, 11 mammal species, two reptile species, and one amphibian species.[6]

The list of migratory game birds includes species of ducks, geese (including brant), doves, rails, woodcock, and snipe. Mammal species that are legally hunted include white-tailed deer, rabbit, squirrel, muskrat, and red fox. Other game species that are monitored or managed to expand their numbers include wild turkey (*Meleagris gallopavo*) and northern bobwhite quail (*Colinus virginianus).*

Delaware's diverse freshwater and marine aquatic habitats support a number of fish and shellfish species that are economically valuable for commercial and recreational harvest. The Delaware Bay has more than 200 resident and migrant fish species. A few of these important resources include: striped bass (*Morone saxatilis*), American shad (*Alosa sapidissima*), American eel (*Anguilla rostrata*), eastern oyster (*Crassostrea virginica),* blue crab (*Callinectes sapidus),* and horseshoe crab (*Limulus polyphemus*).[7]

The Delaware Wildlife Action Plan 2007-2017 addresses conservation strategies for all wildlife, including fish, invertebrates, and marine species, but does not address conservation strategies for individual plant species. The plan focuses on conservation issues and actions that affect habitats and notes which animal species of greatest conservation need are associated with each habitat type. The plan identifies more than 450 animal "species of greatest conservation need." This designation is partially based on assessments by the Delaware Division of Fish and Wildlife, which tracks species distribution and abundance using internationally recognized natural heritage methodologies.[d] Species of greatest conservation need are indicative of the overall diversity and health of the state's wildlife resources. Some may be rare or declining, others may be vital components of certain habitats, and still others may have a significant portion of their population in Delaware. Eighty-six animal species are listed as State Endangered, including 21 birds, eight reptiles, three amphibians, nine mammals, seven fish, seven freshwater mussels, and 31 insects.

8.1.2. Beach and Dune Ecosystems

Delaware's beach and dune ecosystems include estuarine and ocean beach, dune and dune-swale wetland habitats found along the tidal shoreline of Delaware Bay and the Atlantic Ocean. These habitats are subjected to variations in salinity, wave energy, and substrate. All of these areas are composed of sediments that were either deposited during or reworked from previous higher and lower sea levels. The following summary describes three areas where the beach and dune habitats are found.

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d Natural Heritage Methodology is described further in the Nature Serve web page: http://www.natureserve.org/prodServices/heritagemethodology.jsp

- The *Delaware Bay* estuary hosts beach and dune habitats that are interconnected with extensive tidal marshes interspersed with tidal creeks and rivers. Wave energy increases along the central and southern section of Delaware Bay. In the central section of the bay, beaches are generally narrow with broad, intertidal flats; dunes are sparse and low-lying. Toward the mouth of the bay, beaches are generally wider and often flanked by high, vegetated dunes. Erosion rates along the shoreline are highly variable, with rates of shoreline retreat ranging from less than 2 feet per year to more than 17 feet per year.[8]

- *Cape Henlopen* is a narrow spit of land located at the mouth of Delaware Bay that includes beach and dune habitats of both the bay and Atlantic Ocean. Sand transported by ocean currents is expanding the spit northward. The beaches and dunes at Cape Henlopen are naturally accreting (building up land by deposition of sand or sediment). The Great Dune, a major feature at Cape Henlopen situated perpendicular to the Atlantic shoreline, is migrating southward at a rate of up to six feet per year, altering maritime forest habitat as it progresses.[9]

- The *Atlantic Ocean* beach and dune habitats south of Cape Henlopen are either backed by headlands (at Rehoboth Beach and Bethany Beach) or are found on the bay mouth barriers that separate the ocean from the Inland Bays. These beaches and dunes serve as a line of defense against storms for the adjacent marsh habitats that rim the eastern portion of Rehoboth, Indian River, and Assawoman Bays. Dunes form a vegetated ridge that runs parallel to the shoreline. The Atlantic Ocean beaches and dunes are exposed to higher wave energy than their Delaware Bay counterparts, and in both areas (Delaware Bay and Atlantic Ocean), the beaches and dunes can be overtopped or breached during storms.

Beach and dune habitats are strongly influenced by the dynamic conditions that continually shape and reshape their physical and biological features. Winds, waves, and tides are three forces creating constant change. Coastal storms amplify the effects of winds, waves, and tides by increasing height and strength of waves as they reach higher on the shore and remove sand from the dune face to be transported offshore onto sandbars. In extreme storms, the dunes may be breached or overtopped, moving sand landward. The forces of water and wind create a highly dynamic system in which beach and dune habitats can be eroded, inundated, or relocated as sand and sediment are moved alongshore.[10]

Beach and dune habitats support a rich diversity of plants and animals adapted to a highly dynamic environment. Plant material and debris that wash up on the sandy beach provide organic matter for scavenging amphipods such as sand fleas, which, in turn, are an important food source for shorebirds and crustaceans. Dune habitats offer food and shelter for numerous insects and other arthropods, including beetles, butterflies, and spiders, as well as important nesting habitat for diamondback terrapins.[11] Delaware Bay and Atlantic Ocean beaches and coastal habitats provide important habitat for many species of gulls and shorebirds. Along Delaware Bay, beach and dune habitats offer an abundant food source for many migratory species, such as the red knot (*Calidris canutus)* and other shorebirds that feed on the eggs of horseshoe crabs in the spring. The Delaware Bay is the largest spring staging area for migratory shorebirds in eastern North America; during their spring migration, an estimated one million shorebirds use these beach, marsh, and mudflat habitats. Ninety-five percent of these birds are represented by four species: red knots, ruddy turnstones, semipalmated sandpipers, and dunlins.[12] Beaches also provide important nesting habitat for several species, such as least tern (*Sternula antillarum*) and piping plover *(Charadrius melodus*).

Dune systems are highly diverse habitats, supporting plants and animals adapted to harsh conditions, including high temperatures, inundation by salt water and salt spray, and continual movement of sand. Beach and foredune habitats are generally vegetated with small annuals. Foredune and backdune areas may be dominated by American beachgrass (*Ammophila breviligulata)* and other salt- and drought-tolerant plants. Interdunal swales form where water collects behind dunes, and are characterized by a variety of shrubs, sedges, and rushes. More than 20 species of rare plants are found in these wetland habitats.[13] Secondary dunes support maritime forests of loblolly pine (*Pinus taeda*) and thickets of native shrubs.[14]

Beach and dune habitats act as a protective buffer from the direct impacts of storm waves and surges. During storm events, wave energy is diffused by moving sand and reconfiguring the beach and dunes. Although bay beaches are subject to less wave energy than ocean beaches, adjacent tidal marsh habitats also help absorb the impacts of wave action and high tides. In addition to these natural forces, human activities add to the complexity of these highly active ecosystems.

8.1.3. Wetland and Aquatic Ecosystems

Wetlands are perhaps Delaware's most significant natural feature, covering one-fourth of the state, with a total of approximately 320,000 acres.[15] An estimated 47 percent of wetlands are located in Sussex County, 38 percent in Kent County, and 15 percent in New Castle County. Wetland habitats include a wide range of types – tidal, nontidal, freshwater, brackish, and saltwater, and include coastal wetland impoundments, vernal pools, Coastal Plain seasonal pond wetlands, peat wetlands, and Piedmont stream valley wetlands. Wetlands are found along the shores of the Delaware Bay and Inland Bays, along rivers, streams, and ponds, and in forests and fields throughout the state.

According to the U.S. Fish and Wildlife Service's wetland classification system, wetlands occur in five ecological systems. The majority of Delaware wetlands fall into two systems:[16] *Freshwater wetlands* include freshwater floodplains, headwaters, and isolated wetlands and ponds. These represent the predominant wetland types in Delaware, comprising roughly 76 percent of the state's wetlands; more than 85 percent of these freshwater wetlands are forested. *Estuarine wetlands*, where freshwater mixes with seawater, make up more than 23 percent of the state's wetlands; salt marshes are the dominant type of estuarine wetlands.

Wetlands can receive water from many sources: precipitation, surface runoff, groundwater discharge, and tides. Some wetlands are inundated daily, whereas others are wet seasonally. Some forested wetlands rarely have surface water, but have high water tables near the surface that keep the soils wet for extended periods. Wetlands are generally defined by hydric (waterlogged) soils that result from repeated or prolonged saturation. This saturation creates anaerobic (oxygen-deficient) conditions; plants must by adapted to hydric soils (hydrophytes) to survive and reproduce in these habitats.

Wetlands perform critical functions such as buffering inland areas from storm surge, providing water storage to reduce flooding, filtering contaminated runoff from upland areas, limiting sediment inputs into aquatic systems, and sequestering carbon.[17] Wetlands also provide organic matter, which serves as food for aquatic invertebrates. Estuarine ecosystems, including marsh and aquatic habitats, are among the most productive in the world, and provide spawning and nursery habitat for numerous fish and shellfish species. (Wetland ecosystem services are also discussed in Chapter 9, Infrastructure.)

Delaware's aquatic habitats include streams, rivers, ponds, reservoirs, bays (Delaware Bay and Inland Bays), and the Atlantic Ocean, including the open waters of these habitats and submerged bottom substrates, submerged aquatic vegetation, and exposed riverine and estuarine mud, sand, and gravel bars. In the Piedmont region of the state, aquatic habitats are freshwater. In the Coastal Plain region, there are dozens of freshwater millponds that were formed by damming streams in the 18th and 19th centuries. Upstream from millpond dams, the headwater wetlands and steam segments are also freshwater. Downstream from millpond dams, streams and rivers are generally tidal and range from freshwater to brackish or saltwater. Salinity varies, depending on the distance from the coast and distance up the estuary. Historically, stream channelization and ditching were practiced extensively on the Coastal Plain to support agriculture; the vast network of ditches is still evident today, particularly in Sussex County.

Freshwater streams, rivers, and ponds support a variety of warm-water species that are both ecologically and economically important. Freshwater mussels provide an important ecological function by filtering the water, and game fish such as largemouth bass (*Micropterus salmoides*) provide excellent recreational angling opportunities.

The species found in Delaware's streams and rivers are highly influenced by both topography and water chemistry. The Piedmont physiographic region has faster flowing water than streams found on the Coastal Plain, resulting in fish communities that are strikingly different between these two regions of the state (**Figure 8.3**). On the Coastal Plain, the slow-moving waters accumulate higher amounts of tannin from adjacent vegetation communities, making the water more acidic and ideal for certain species such as the blackbanded sunfish (*Enneacanthus chaetodon*).

Delaware also has managed wetland and aquatic habitats that provide wildlife habitat value even though they were not naturally formed. Many streams on the Coastal Plain were dammed for milling purposes in centuries past. Although their original function was for powering mill operations, today millponds also function as habitat for waterfowl, fish, mussels, and other aquatic species. Millpond dam structures also prevent brackish water from entering the freshwater aquatic system farther upstream, protecting Atlantic white cedar and bald cypress wetland habitats. Other ponds have been created or enlarged with dams to provide recreational fishing opportunities. In addition, ponds have been built to provide stormwater management for new development; these are technically considered wetlands, but provide very limited ecological function compared to natural wetlands.[18]

Coastal impoundments are managed wetland habitats where low-level dikes and water-control structures have been constructed to restrict, retain, or exclude water over a selected area.[19] Delaware has an extensive complex of coastal impoundments along the Delaware Bay, Atlantic Ocean (Gordons Pond), and Little Assawoman Bay. Impoundment wetland habitats vary from fresh to brackish, depending on how the water depths and flows are controlled. Water-level management often varies seasonally to benefit particular species or meet specific conservation goals. For example, water levels may be kept high in winter and drawn down slowly to support invertebrate populations, an important food source for migratory waterfowl and shorebirds in spring. In summer, water levels are often kept low to allow vegetation to grow; the impoundments are then flooded to provide food and habitat for waterfowl on their return migration in fall.

Delaware's wetland and aquatic habitats are often described by watershed basins (**Figure 8.4**). A watershed basin is the area of land that drains into a stream, river, or bay.

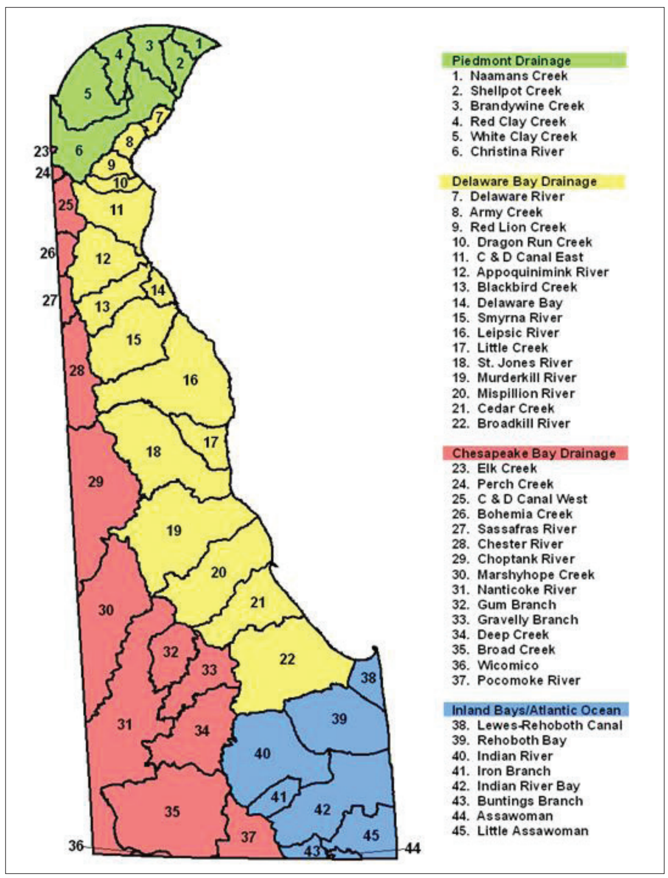

Figure 8.4. Delaware basins and watersheds.
Source: Delaware Department of Natural Resources and Environmental Control, Water Quality Monitoring Network portal.

Delaware Bay and Estuary

The Delaware River watershed covers 814 square miles of Delaware's land area, and includes the watersheds of numerous tributary streams and rivers, such as Blackbird Creek, Murderkill River, Leipsic River, and Appoquinimink River.[20] Most of the freshwater wetlands in Delaware's portion of the Delaware Basin consist of bottomland forest, swamps, riparian wetlands, and freshwater marshes. The Delaware Bay coast is dominated by tidal estuarine wetland habitats, characterized by salt or brackish waters. These habitats are found along the coast and in coastal rivers upstream to the point where salinity levels fall below 0.5 parts per thousand. The largest portion of tidal wetlands is salt marsh habitat dominated by salt-tolerant grasses such as *Spartina* spp. Coastal Plain seasonal pond wetlands are found farther inland, primarily in the Delaware Bay drainage, but are also in the Chesapeake and Inland Bay drainages. These are shallow, seasonally flooded freshwater wetlands, usually less than an acre in size. These unique wetland communities support 45 rare and uncommon plant species and a high diversity of amphibians, including five salamander species and 13 frog species, including the barking tree frog (*Hyla gratiosa)*.[21]

Chesapeake Basin

In Delaware, the Chesapeake Basin drains approximately 769 square miles, and includes portions of the Choptank River, Nanticoke River, Marshyhope Creek, and Broad Creek watersheds. Almost all (99 percent) of the wetlands in Delaware's portion of the Chesapeake Basin consist of bottomland forest, swamps, riparian wetlands, and tidal and nontidal freshwater marshes. Several unique and threatened wetland types are found in Delaware's portion of the Basin, including bald cypress *(Taxodium distichum)* and Atlantic white cedar *(Chamaecyparis thyoides)* forested wetland habitats. The Chesapeake Basin also supports riverine aquatic and submerged vegetation habitats, which are found in stream channels and backwaters throughout the Coastal Plain, and most extensively in the Nanticoke watershed.[22]

Delaware Inland Bays

This 292-square-mile watershed consists of three coastal bays and their tributary rivers, including Rehoboth, Indian River, and Assawoman Bays. The Inland Bays basin is a matrix of salt marshes, tidal flats, and winding creeks where freshwater mixes with seawater that flows into the bays through Indian River Inlet. Wetlands cover 39 percent of the Inland Bays watershed and include both tidal and nontidal wetlands as well as rare wetland communities such as Atlantic white cedar swamps.[23] Nearly 10,000 acres of salt or brackish tidal wetlands provide habitat for waterfowl and migratory birds and nursery habitat for fish, and also serve important ecosystem functions, including regulating water quality by filtering nutrients and sediments.[24] Nontidal wetlands include flat wetlands, generally found at the headwaters and between streams, and riverine wetlands, located adjacent to streams. These poorly drained wetlands retain heavy precipitation and are thus helpful in reducing downstream flooding. Peat wetlands are another rare habitat found in only two locations in the Inland Bays area.[25]

Piedmont Basin

The Piedmont Basin covers 605 square miles in Delaware and Pennsylvania, and includes the Christina River, Brandywine Creek, Red Clay Creek, and White Clay Creek watersheds. Wetlands in the basin are generally associated with the headwaters of streams or with tidal estuaries, and with seasonally flooded depressions. Forested wetlands are the most common wetland habitat in the Piedmont Basin. Floodplain forests dominated by red maple (*Acer rubrum*) are found throughout the Coastal Plain portion of the basin. Floodplain forests dominated by American sycamore (*Platanus occidentalis)* and box elder *(Acer negundo)* are found along Piedmont streams such as White Clay Creek and Red Clay Creek. Headwater riparian wetlands are ecologically important for helping to maintain water quality through sediment trapping and uptake of nitrogen and phosphorus.

8.1.4. Forest Ecosystems

Forests cover approximately 30 percent of Delaware's land area, an estimated 371,000 acres, with a diverse variety of forest and woodland community types. Delaware represents the northern extent of some forest species, such as loblolly pine (*Pinus taeda*) and bald cypress (*Taxodium distichum)*, and supports populations of northern species such as sugar maple (*Acer saccharum*) that are generally not found south of Delaware except at higher elevations.

Historically, Delaware's forests covered an estimated 90 percent of the state. European settlers cleared forests for timber, agriculture, and settlements, so that by the 20th century, forest cover ranged between 370,000 and 450,000 acres. Although the state's total forest acreage has remained relatively stable in the past three decades, forest assessments indicate that average forest tract size is declining and forest habitat is becoming more fragmented, largely as a result of development. The average size of forest ownership has declined from 30 acres in 1975 to less than 10 acres today. The Delaware Forest Service estimates that only 20 percent of all forest parcels are 500 acres or larger.[26] In addition, seedling and sapling forests represent less than 25 percent of forested land. These younger forests are needed to replace older forests as they are harvested or lost to storm damage or natural mortality. Seedling and sapling forests are also important habitat for certain species, such as American woodcock *(Scolopax minor)*.[27]

Forests provide a wide range of ecosystem functions that help maintain water quality for both surface water and groundwater. Riparian buffers and forested wetlands help filter surface water, by slowing runoff and trapping sediments and pollutants before they reach waterways. Forests are important for protecting water quality in groundwater recharge areas. Forests also serve to moderate local climate conditions; for example, riparian buffers that shade streams help to maintain cooler water temperatures, benefitting fish and invertebrate aquatic species. Forest ecosystems can also function as carbon sinks; the Delaware Forest Service estimates that Delaware's forests store more than 20 million tons of carbon.[28]

Delaware forest habitats support a number of rare and sensitive species, including a diversity of bird species. In Delaware, 113 bird species are known to depend on forest habitat for breeding, migrating, or overwintering; four of these are state-listed as endangered. A number of bird species are considered "forest interior dwelling species," meaning they require large blocks of forest habitat to successfully reproduce. Smaller fragments of forest, with more edge habitat, increase competition for suitable nest sites and food resources with edge-tolerant species. Greater edge-to-interior ratios increase the risk of predation, especially for ground or near-ground nesting birds. Smaller patches also expose many forest interior birds to higher rates of nest parasitism by opportunistic brown-headed cowbirds.

Forest habitats, as with other ecosystem types, can be described or categorized in different ways. The Delaware Forest Service recognizes forest types based on inventories by the U.S. Forest Service through its Forest Inventory and Analysis (FIA) program. The FIA is organized by species associations and identifies six forest type groups in Delaware: loblolly-shortleaf; oak-pine; oak-hickory; oak-gum-cypress; elm-ash-red maple; and northern hardwoods.[29] Based on these categories, the FIA estimates that the oak-hickory group makes up more than half of the forested area in Delaware, and pine and oak-pine types comprise approximately one-fourth of the total forest area. Minor hardwood components (gum, maple, etc.) occupy the remaining 15 percent of the forested acreage.[30]

The Delaware Wildlife Action Plan 2007-2017 uses *The Natural Communities of Delaware,* which is based on the National Vegetation Classification System, as a wildlife habitat classification framework. This system provides a more detailed classification than FIA, and is also based on dominant species associations. These forest habitats are summarized below with highlights of some of the rare and unique forest types found in the state.

Upland Forests

Piedmont upland forests are found in the northern part of Delaware on steep slopes in stream valleys and on adjacent rolling hills. The canopy is a mix of deciduous species, such as tulip poplar, American beech, oaks, and hickory. Piedmont upland forests often support a rich flora of spring wildflowers, which include a number of state rare species. Coastal Plain upland forests are found in central and southern Delaware on dry or moist, but not wet, soils. These forest types vary from deciduous oak-hickory communities to coniferous stands dominated by loblolly pine (*Pinus taeda*). Ancient Sand Ridge forest is found in the Nanticoke River area on relic sand dunes that originated before the last glacial period, and is generally dominated by Virginia pine (*Pinus virginiana*) and southern red oak (*Quercus falcata*). This rare forest type provides vital habitat for caterpillars of the frosted elfin (*Callophrys irus),* a globally rare butterfly whose caterpillar feeds exclusively on the wild lupine (*Lupinus perennis*), which grows only in this forest community.

Forested Wetlands

This group of forest types occurs in seasonally flooded areas and in floodplain depressions with saturated soils. Red maple (*Acer rubrum*) is found in several species associations with green ash, sweet gum, and bald cypress. Atlantic white cedar (*Chamaecyparis thyoides*) nontidal wetlands are found only from southern Delaware along slow-flowing streams with poorly drained soils. These forested wetlands provide habitat for several rare plant species, such as the swamp pink (*Helonias bullata*), which is federally listed as threatened. Bottomland forest types such as baldcypress-red maple-swamp black gum swamp habitat have also experienced declines due to logging and extensive drainage as a result of ditching and stream channelization. Isolated forest wetlands can provide important refuge for wildlife, particularly when strategically located to serve as a habitat corridor to link larger forest blocks. Freshwater tidal forested wetlands are found in central and southern Delaware on systems such as the Murderkill River in Kent County and the Nanticoke River in Sussex County. Freshwater tidal forests are either a mix of red maple and pumpkin ash (*Fraxinus profunda*), or Atlantic white cedar.

8.2. Climate Change Impacts to Ecosystems and Wildlife in the United States

Climate change will have direct and indirect impacts on the natural world at all levels: species, habitats, and ecosystems. Responses to changes in temperature, precipitation, extreme weather events, and sea level rise will affect the distribution of species and functions of ecosystems in many different ways. Some of these changes, such as poleward shifts in species ranges, have already been observed. In addition, the impacts of climate change will be compounded by impacts from other external stressors, such as habitat fragmentation, invasive species, and pollution.

8.2.1. Biodiversity and Ecosystem Function

The diversity of living organisms (biodiversity) is fundamental to ecosystem structure and function. Impacts to individual animal or plant species can have far-reaching effects on the role that species plays in an ecosystem. For example, a top predator species may fill a key function in the food chain, keeping prey populations in check, and a migratory insect species that acts as a critical pollinator may be vital to the propagation of the plants it pollinates. Thus, the decline or loss of biodiversity as a result of climate change can trigger larger changes at the habitat and ecosystem level.

Many scientific studies indicate that the rate of climate change and its magnitude may exceed the ability of many species to adjust quickly enough to survive, resulting in localized extinctions and loss of overall biodiversity.[31] The response to climate change of an individual species reflects its life cycle, sensitivity to change, and ability to migrate or move in pace with the changing environmental conditions. In addition, the availability of migratory pathways or corridors is critical for many species. Entire communities do not shift at the same time or in the same ways; therefore, significant changes in species composition and ecosystem function can result from varied responses to climate change.[32]

8.2.2. Responses to Change

The ways in which species and populations respond to climate changes can vary widely. Differences in how organisms respond to climate change — their adaptive capacity — will lead to some species benefitting, by expanding their range and/or increasing population, and other species declining. In the northeastern United States, for example, some forest types such as oak-hickory are expected to expand, while maple-beech-birch forests are expected to contract.[33]

Responses to climate change that have already been observed include changes in geographic range and the timing of life cycle events such as migration and reproduction. Numerous studies show shifts in the geographic range of species in response to increasing temperatures. As the climate warms, species may shift poleward (north in the northern hemisphere) or to higher elevations. For example, winter bird counts taken in the United States over the past 40 years showed a significant shift northward for more than half of the species tracked (177 of 305); nearly 20 percent of the species recorded had shifted more than 100 miles to the north.[34] These northward shifts are also being observed in ocean habitats. In U.S. waters, marine species are shifting northward, and changing distributions of both cold- and warm-water fish species have been recorded.[35]

Changes in bloom time, migration, and nesting are also well documented. Some changes in life cycle activities are triggered by the increasing length of the growing season. Global satellite data show that the onset of spring across temperate latitudes has advanced by 10 to 14 days over the past two decades.[36] However, a species' ability to adjust geographically or temporally does not guarantee survival. The timing of these shifts can be critical for ecologically linked species, potentially resulting in a mismatch between species and the resources they need to survive. Migratory birds, for example, depend on food supply in breeding territories, wintering grounds, and throughout their migratory path. The earlier onset of spring may alter the optimum timing for arrival of birds that rely on peak food availability to support their breeding cycle.

In addition to being an existing external stressor, new invasive species and diseases may emerge as they benefit from changing climate conditions, readily establishing in new areas and outcompeting native species for resources. The spread of new diseases and pathogens may also be enhanced by changing climate conditions, potentially affecting native species and humans. **Table 8.1** summarizes the potential ecological impacts in response to climate change.

8.2.3. Ecosystem Thresholds

There has been considerable research on how species and natural communities respond and adapt to climate change impacts. In addition, some scientific analyses are examining the complexities of how the structure and function of ecosystems are affected by large-scale change. Two key concepts that describe these consequences of climate change are *ecosystem resilience* and *ecological thresholds*.

Ecosystem resilience describes the "ability to adapt naturally" to environmental changes; in other words, the species within an ecosystem and the ecosystem as a whole have the capacity to adapt in pace with changing conditions. Resilience is also described in terms of how much disturbance an ecosystem can tolerate before changing to a different state. Global assessments of climate change widely recognize that climate change acts in combination with other human-induced pressures, such as resource extraction, habitat fragmentation, and pollution.[37]

An ecological threshold can be defined as the point at which there is an abrupt change in an ecosystem's condition or function that is potentially irreversible. This concept recognizes that an ecosystem's ability to adapt to gradual change (resilience) can be disrupted when a threshold,

Table 8.1 Potential ecological impacts in response to climate change

Observed or projected physical change	*Examples of potential impacts on biodiversity*
Increased temperature	• Species and population range shifts • Changes in phenology leading to alteration or loss of biotic interactions
Changes in annual and seasonal precipitation	• Changes in species composition of communities and habitats
Increased frequency of extreme events	• Mortality resulting from flooding after storms • Damage or mortality resulting from drought or heat waves
Changes to hydrologic regimes	• Reduced streamflow affecting species population persistence and community composition
Changes to fire regimes	• Changes in species composition of communities
Ocean acidification	• Change in water chemistry affecting calcification rates of marine organisms
Sea level rise	• Habitat loss and fragmentation from coastal erosion or inundation
Increases in ocean stratification	• Reduced productivity of pelagic ecosystems
Changes in coastal upwelling and/or ocean temperatures	• Changes in productivity of coastal ecosystems and fisheries • Species and population range shifts and/or changes in phenology leading to alteration or loss of biotic interactions

Adapted from: National Climate Assessment (2012).[38]

or tipping point, is crossed. Small changes in climate can trigger large responses through positive feedbacks, which amplify or increase the initial change in the same direction (see Chapter 1, Section 1.5, Climate 101). Threshold crossings or transitions create a domino-like effect, so that the failure of one component in an ecosystem triggers instability throughout the rest of the system.

The combined effects of climate change and other human-induced stressors can push an ecosystem toward ecological thresholds. For example, the Chattahoochee-Apalachicola River basin in Alabama, Florida, and Georgia is an important ecosystem for fisheries that depend on access to tributaries for feeding and spawning. Increasing water withdrawals for human use, in combination with climate change trends, are creating conditions of water stress for many aquatic species. It is estimated that minimum river flows may fall below threshold levels in the summer by mid-century, potentially eliminating vital habitat for fish populations and significantly changing the ecosystem and its function.[39]

Although the conceptual understanding of ecological thresholds is still developing, the complexity of ecosystem dynamics makes it very difficult to predict the tipping point for a given ecosystem. Ecosystem resilience is likely to vary widely among different types of ecosystems and under different combinations of climate change drivers and other stressors. In its Fourth Assessment Report (2007), the Intergovernmental Panel on Climate Change stated that the resilience of many ecosystems is likely to be exceeded by "an unprecedented combination of change in climate, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification) and in other global change drivers (especially land-use change, pollution and over-exploitation of resources), if greenhouse gas emissions and other changes continue at or above current rates.[40]

8.3. External Stressors

Species and ecosystems are already challenged by a number of human-caused stressors, including habitat loss and fragmentation, altered hydrology, water quality impacts, invasive and nuisance species, and other resource and recreational uses. The impacts of climate change are likely to add to or exacerbate other stressors, increasing the vulnerability of those ecosystems facing multiple pressures.

Habitat loss and habitat fragmentation are leading factors in loss of biodiversity. Habitat loss eliminates feeding, nesting, and shelter areas for resident and migrant wildlife species. Habitat fragmentation degrades the quality of habitat and increases exposure of wildlife to predators and invasive, nonnative species. The primary cause of habitat loss is residential and commercial development. Land use changes that accompany population growth have direct and indirect effects on wildlife and ecosystem resources. These impacts result from changes in land use (conversion or development of natural habitat) or from management or operations of agriculture, transportation, or industrial activities (degrading habitat quality).

Altered hydrology that accompanies development and other land use changes can have long-term impacts on both aquatic and terrestrial habitats. Residential and commercial development practices increase impervious surface, which leads to degraded streams and wetlands as a result of polluted surface runoff, and reduces groundwater recharge. Impervious surfaces and other hydrologic changes, such as filling, ditching, and draining of wetlands, increase streamflow rates, raise water temperatures, and degrade water quality. Surface water withdrawals can reduce streamflow, especially during summer periods of peak demand. Loss of vegetation along streams and waterways as a result of development can also increase water temperatures in streams and rivers, which can harm fish and invertebrate species and trigger algal blooms. Dredging of waterways also has significant impacts on marine and estuarine habitats.

Water quality impacts are associated with agriculture, industry, new construction, and land use practices related to commercial and residential development. In many states, including Delaware, water quality is already impaired by excess nutrients from wastewater treatment plants, septic systems, agricultural runoff, pet waste, and fertilizers. Sedimentation from land-clearing activities (for development, agriculture, or forestry) affects water quality by decreasing dissolved oxygen levels and by reducing the penetration of sunlight, which affects aquatic vegetation. Nutrients from fertilizer use in suburban, urban, and agricultural landscapes leads to nutrient enrichment, algal blooms, and lower oxygen levels.

Invasive and nuisance species can have direct and indirect effects on wildlife and ecosystems. Invasive plant species displace native plants and reduce plant diversity. Nonnative insect species can have devastating effects on forests and other habitats. More than 450 nonnative forest insects are known to occur in the United States. Nonnative aquatic species compete with native species, leading to a decline in species diversity in freshwater systems. Native species can also become nuisance species when populations expand due to lack of predators or increasing food opportunities. For example, white-tailed deer *(Odocoileus virginianus)* thrive in rural and agricultural landscapes; their increasing numbers lead to intensive browsing, reducing vegetation and impairing the regeneration of forest trees and understory shrubs. The snow goose *(Chen caerulescens)* has also become a nuisance species in areas where excessive numbers degrade tidal wetlands, streams, and ponds due to their feeding habits.[41]

Other human activities that represent external stressors on species and habitats include resource use and recreation. *Resource uses* include surface and groundwater withdrawals; reducing freshwater flows can impair recharge and deplete streamflows, leading to degradation or loss of aquatic habitat. Recreational and commercial harvest of fish and game species can put direct pressure on population size and also have indirect impacts, such as fishery bycatch or ingestion of lead shot. *Recreational activities* can cause disturbance to wildlife or degrade habitats. For example, wakes from pleasure boats and personal watercraft can disturb shorebirds and waterfowl, and can cause increased shoreline erosion.

8.4. Potential Impacts of Climate Change to Delaware's Ecosystems and Wildlife

8.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. Species and habitats will be responding to the interaction of these factors, which complicates an assessment of the impacts Delaware's ecosystems and wildlife may experience. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide (CO_2) and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar. The growing season is also projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099 (**Figure 8.1**).

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

Precipitation changes

- Precipitation is projected to increase, particularly in winter (**Figure 8.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 8.2**).

8.4.2. Climate Impacts to Species and Ecosystems

The Intergovernmental Panel on Climate Change defines ***vulnerability*** as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity."[42] ***Sensitivity*** includes intrinsic characteristics of a species, such as habitat specialization, physiological tolerances, and dispersal ability. ***Adaptive capacity*** describes the ability of a system (or species or population) to adjust to adjust to climate variability and extremes.[43]

Plant species are affected by increasing temperatures, leading to altered bloom times, changes in reproductive cycle, and potential mismatch of timing with pollinator species. Plant communities are likely to be affected by increased temperature combined with drought, leading to stress that increases their vulnerability to insect pests and pathogens. Invasive species may be an increasing problem in many plant communities. Higher levels of atmospheric CO_2 stimulate plant growth, and some studies have shown that invasive plants respond with greater growth rates than native plants. In addition, invasive plant species are often able to tolerate a wide range of environmental conditions and are better able to move into new locations.[44]

Wildlife species will face alterations in habitat type, quality, timing and availability of food sources, abundance of pests and diseases, and other stressors related to changes in temperature and precipitation. Some species will adapt to changing conditions, and some will even thrive. Other species will have to change behaviors or migrate to new areas to adapt. Climate change will compound other environmental stressors, such as pollution or competition from invasive species, making it difficult to predict the impacts of climate change on particular wildlife species. Changes in species distribution and abundance have already been observed; many northeastern U.S. birds are expanding their range northward, a shift that correlates with regional climate change. Research on forest bird species indicates that many resident forest birds have increased in abundance, a trend that is projected to continue. In contrast, short-distance migrant birds are projected to decline, and neotropical migrant species will likely see both increases and decreases, depending on their geographic range and conditions in their migratory habitats.[45]

Ecosystems represent unique assemblages of species living within a physical environment. When the environment changes – physically, biologically, or chemically – the composition and abundance of species and the overall suitability of the habitat is likely to change as well. Climate change is one of many drivers affecting environmental conditions that can have subtle or dramatic effects on ecosystems.

This summary focuses on three broad categories of ecosystem types in Delaware: beaches and dunes, wetland and aquatic systems, and forests. The potential vulnerabilities described here are necessarily general; however, this section is intended to illustrate some examples of ecosystem issues that Delaware is already coping with, and which could present vulnerabilities for the state with increasing impacts of climate change.

8.4.3. Species Impacts – Changes in Habitat and Hydrology

Aquatic and wetland-dependent species will be affected by climate change impacts that result in changes in hydrology and habitat loss or fragmentation. Some species may be able to adjust to changing conditions by migrating upstream, downstream, or landward, but these adaptations may be impaired if suitable habitat is not available for migration. For example, some tidal plant and animal species have specific ranges of tolerance for water temperature and salinity; the survival of these species may depend on critical habitat shifting in pace with climate change impacts, such as increasing temperatures and sea level rise.

Species with very restricted ranges and isolated populations are facing increasing risks, with climate change compounding other stressors. For example, amphibians are already sensitive to changes in temperature and precipitation. Because most amphibians reproduce in aquatic habitats, their breeding success depends on the availability of water at specific times. Increasing temperatures

Delaware at the Crossroads – Loss of Genetic Diversity

Delaware's unique geographic location is a key to the state's impressive diversity of plants and animals. Situated at the "crossroads" between New England, the Mid-Atlantic, and the Southeast, Delaware supports plant species at the northern and southern extremes of their geographic ranges. These populations of plants at the edges represent part of the genetic diversity of that species to tolerate a range of environmental conditions.

For example, southern blue lobelia *(Lobelia elongata)* is found in freshwater tidal wetlands in many southern and southeastern states. Populations of the southern blue lobelia in Delaware, at the northern extent of its range, are able to tolerate colder winters than southern populations of the same species. Thus, the Delaware population of the southern blue lobelia represents a genetic variation that allows the plants to persist under local climate conditions.

Genetic diversity is critical to the long-term viability of a species. Changing climate conditions may not threaten the survival of a species throughout its range, but the loss of individual populations can mean the loss of part of that species' genetic variability.

Assessing Vulnerability – Bird Species at Risk

Vulnerability is described as a function of the sensitivity of a particular system or species to climate changes, its exposure to those changes, and its ability to adapt to those changes (see Section 8.4.2).

Vulnerability assessments conducted at the national and state level indicate that the highest proportion of vulnerable bird species is in bird groups (taxa) that use rocky shorelines, beaches, coastal wetlands and estuaries, and nearshore waters. An assessment conducted by the U.S. Department of the Interior found that bird species in ocean and coastal environments were most vulnerable to climate change impacts.[e] In Delaware, a few examples of potentially vulnerable species are noted below.

The black rail *(Laterallus jamaicensis)* is a habitat specialist that requires wetland habitat with specific vegetation and salinity range. This species is found in coastal salt and brackish marshes dominated by Spartina patens, and nests in areas of high marsh that are flooded only during extreme high tides. These habitats are particularly vulnerable because, with sea level rise, they will be squeezed between the twice-daily inundated low salt marsh (dominated by Spartina alterniflora) and the uplands. Sea level rise and increasing exposure to storm surge will increase the vulnerability of this already-rare species.

The red knot *(Calidris canutus rufa)* arrives on Delaware Bay shores every spring on its migratory route between its wintering habitat at the tip of South America and its summer Arctic nesting grounds. The arrival of red knots in Delaware coincides with the spawning of horseshoe crabs *(Limulus polyphemus)*, whose eggs provide a critical food source for the knot on its 9,300-mile journey. As the climate warms, changing water temperatures may trigger an earlier (or later) spawning, resulting in a potential mismatch between the timing of food availability and the arrival of red knots and other migratory birds. In addition, sea level rise and accelerated coastal erosion could affect the sandy beach habitat needed by both birds and horseshoe crabs.

and more frequent drought may reduce the size and abundance of ephemeral ponds, increasing competition for breeding habitat. Additionally, changes in hydrology and water availability could affect (positively or negatively) the transmission of amphibian and reptile diseases such as chytridiomycosis and ranavirus.

Changes in precipitation and hydrology can affect both prey and predator species. Bats, for example, feed primarily on insects, and many insect prey species depend on aquatic habitats for reproduction. Reductions in summer streamflows will increase water temperatures and reduce available habitat for temperature-sensitive aquatic species, such as smallmouth bass (*Micropterus dolomieu*).The timing of snowmelt affects spring runoff in headwater streams of the Delaware River watershed; fish species that spawn in spring may be particularly vulnerable to changes in timing and amount of streamflow.[46]

Changes in precipitation will also affect water quality, temperature, and salinity, which directly affect aquatic species. For example, in very dry and warm years, movement of saline waters farther up the Delaware estuary has increased the incidence of parasites that cause disease in the eastern oyster.[47] Increased frequency of intense storms will increase surface runoff into streams and increase streamside erosion, affecting the type and quality of in-stream habitat.

8.4.4. Species Impacts – Extreme Weather and Temperature Changes

Extreme weather events will have direct impacts on many species, especially those facing exposure during critical periods such as nesting or migrating. Beach-nesting birds and migratory shorebirds are among the most vulnerable.[48] Severe storms cause structural damage to forest habitats, and heavy rain events trigger high flows in streams that can destroy aquatic habitats. Flooding associated with heavy rains will also affect upland species, such as ground-dwelling mammals. Increasing temperatures will also affect insect populations, including insect vectors for wildlife disease. For example, outbreaks of hemorrhagic diseases in white-tailed deer, spread by biting midges, have been observed to increase in summer seasons with high heat and drought conditions.

Availability of food is a critical factor that may be altered under changing climate conditions. Small mammals with high energy demands can be affected by even short-term fluctuations in food availability. In addition, bats are hibernating species that are vulnerable when winter temperatures are much higher or lower than their optimal range. Warmer winters could increase periods of arousal from hibernation, depleting their limited energy stores and resulting in stress or starvation.[49] A fungal disease, white-nose syndrome, affects bats during hibernation and has killed millions of cave-hibernating bats. Additional stressors from climate change could further exacerbate an already catastrophic decline.

8.4.5. Beach and Dune Ecosystems

As described in Section 8.1 above, this discussion of Delaware's beach and dune ecosystems includes beach, dune, interdunal wetland, and tidal flat habitats. Beach and dune habitats are already under enormous stress from pollution, habitat fragmentation, land use changes, invasive species, and erosion. Climate change impacts are very likely to compound the existing environmental stresses to coastal wetlands, dunes, and beach habitats.

Though these areas have consistently undergone a series of changes in sea level in the geologic past, today sea level rise is occurring along Mid-Atlantic coasts at higher-than-global-average rates. This higher-than-average rate of sea level rise can be partially attributed to sections of the land base in the mid-Atlantic sinking due to tectonic land subsidence[e], as well as an increasing elevation of sea level. During the 19th century, global average sea level rose approximately seven inches. In the Mid-Atlantic region (between New York and North Carolina), sea level rose about one foot during the 20th century.[50] In addition, there is evidence that the rate of rise is increasing.[51] Sea level rise can exacerbate other coastal hazards, including storm surge, shoreline erosion, wetland loss, and saltwater intrusion.

The coastal zone, which includes beach and dune habitats as well as the wetland habitats, is highly dynamic, and the impacts of sea level rise are more complex than inundation alone. Physical processes of erosion, transport, and accumulation of sand and sediment continually reshape the coastal landscape as waves and currents modify the shoreline. If a sediment balance is not maintained, inundation of coastal areas in response to sea level rise will likely occur in sheltered, low-energy areas, where sediment accretion is limited. Erosion and inundation related to sea level rise and storm surge will have damaging impacts on coastal wetlands, already diminished by habitat loss from other stressors. Beach and dune and wetland habitats will also be affected by changes in precipitation patterns; increased rainfall and more frequent extreme rain events may alter freshwater flows into coastal wetlands, affecting salinity and inputs of sediment and nutrients.[52]

Changes to beach and dune and wetland habitats in response to climate change will be influenced by many factors. Of particular importance is the relative gain or loss of sediment in the estuary. Accretion or erosion of sediments is critical to whether tidal flats, beaches, and dunes expand or shrink.

The barrier beaches and Inland Bay system in southern Delaware are particularly vulnerable to the combined effects of sea level rise and severe coastal storms. Barrier beaches and dunes are subject to overwash from storm surge, especially where there is insufficient sand or sediment available to maintain barrier width and height. With the potential for coastal storms of increasing intensity, barrier beaches and dunes may be increasingly vulnerable to breaching and formation of new inlets. Landward migration of barriers is another potential response to sea level rise and severe storms.

e Tectonic land subsidence refers to the sinking of the Earth's surface on a large scale. In the Mid-Atlantic region this subsidence is a response to changes in the Earth's crust following the retreat of the glaciers at the end of the last Ice Age.

Coastal Impoundments – Planning for Climate Change

Coastal impoundments are areas of upland or wetland habitats where low level dikes have been constructed to restrict, retain, or exclude water over a selected area. Delaware has an extensive complex of coastal impoundments, managed primarily by state and federal wildlife agencies to serve a variety of purposes and habitat functions.a These managed wetlands provide migratory habitat for huge numbers of waterfowl and shorebirds, including roosting habitat for red knots. Impoundments also serve as breeding habitat for many waterfowl, shorebirds, and marsh-nesting birds, including rails and songbird species. Coastal impoundments may also be managed for mosquito control and to support fisheries.

Given their low elevation and location near shorelines, coastal impoundments are vulnerable to the climate change impacts of sea level rise and more frequent and severe coastal storms. Flooding or overtopping of impoundment dikes can dramatically alter the habitat within the impoundment ponds, rapidly changing water depth and salinity. These impacts can lead to the conversion of freshwater impoundments to saline open water habitat. Adjacent upland habitats can also be affected, as evidenced by trees in forested wetlands dying from increased salinity.a Climate change impacts can also complicate management options for impoundments; for example, higher sea levels and extreme rain events combined may limit managers' ability to draw down water levels. In addition, impoundments and their water control systems may suffer structural damage from flooding or storm surge.

As sea level rise and other climate impacts affect Delaware's tidal wetlands and marshes, the inland migration of wetland habitats is likely to be limited. Landward migration may be constrained by land uses, structures, or topography. As a result, management strategies for coastal impoundments need to adapt to changing conditions. For example, one strategy may be to divide large impoundments into smaller units and manage these for varying levels of salinity. This may lead to a transition of some impoundment ponds to salt marsh, while maintaining others as freshwater habitat. Another strategy may be a managed retreat, by creating new impoundments on the landward side of existing ones. Other options being considered for both natural and managed wetlands is the addition of sediment to marsh habitats to support the accretion of soil that helps wetlands keep pace with rising sea level. Dredge materials are one potential source of sediment, which may be coordinated with the Army Corps of Engineers for "beneficial reuse" projects.

The Delaware Division of Fish and Wildlife is coordinating with other state and federal agencies to develop a "climate smart" approach to the management of coastal impoundments under changing climate conditions. Although management practices reflect site-specific needs, long-term planning will address climate change impacts in the context of coastal wetland habitats across the state and throughout the Atlantic Flyway region.

Tidal flat habitats will respond to sea level rise in different ways, depending largely on sediment movement and availability. Where sediment inputs are low, tidal flats will become subtidal habitats and potentially convert to open water as sea level rises. Loss of tidal flats will affect numerous bird species that forage in these food-rich habitats.[53]

Estuarine beaches also play an important role in coastal food webs, particularly for horseshoe crabs that lay their eggs on beaches and intertidal habitats. Delaware Bay beaches and tidal wetlands are critical habitat for more than 40 species of migratory shorebirds. The persistence of estuarine beaches depends on the availability of sediment to replenish eroded lands. Sea level rise and coastal storms may result in increased erosion or decreased sediment availability, which may lead to loss of estuarine beach habitat.[54]

8.4.6. Wetlands and Aquatic Ecosystems

As described in Section 8.1 above, this discussion of Delaware's wetland and aquatic ecosystems includes a wide range of wetland types – tidal, nontidal, freshwater, brackish, and saltwater – and also includes stream and river aquatic habitats.

Climate change impacts from sea level rise, changes in precipitation, and extreme weather events will have significant effects on both freshwater and saltwater wetland habitats. In addition, increasing air temperatures will likely trigger increased water temperatures, affecting biological and chemical processes in the ecosystem. Climate change effects are highly dynamic and affect wetland ecosystems in combination with other external stressors.

Sea levels are projected to rise 1.6 to 4.9 feet (0.5 to 1.5 meters) by 2100. This will have potentially devastating effects on Delaware's coastal habitats, including tidal salt marshes. Some of the state's rarest species depend on the sliver of high marsh between the low marsh and the uplands. Much of this high marsh habitat will be lost if unable to shift inland with salt marsh migration. Some tidal plant and animal species have specific ranges of tolerance for inundation frequency, salinity, and water temperature; the survival of these species may depend on critical habitat shifting in pace with climate change impacts, such as increasing temperatures and sea level rise.

Sea level rise and increased storm surge will affect rates of erosion and accretion in tidal marshes. Climate impacts may lead to wetland losses, landward migration of marsh habitat, or conversion to open water.[55] In sheltered, low-energy coastal areas with limited sediment inputs, shoreline wetlands may be unable to keep pace with rising water levels and thus become submerged.[56]

Changes in precipitation amount and timing may affect water quality with greater swings in salinity. High temperatures combined with drought will increase evapotranspiration, altering soil moisture and increasing salt concentrations that may be intolerable to some marsh species. Temperature and moisture changes, combined with the effects of excess nutrients, will change plant productivity. High nutrient levels promote plant growth above the soil surface while not supporting rhizome growth below the soil, thus making wetland vegetation more vulnerable to loss from storm surges.[57]

Changes in water temperature and chemistry will affect both salt- and freshwater wetlands and aquatic habitats. Higher water temperatures are likely to increase the incidence of harmful algal blooms, which affect the availability of oxygen and light for aquatic species. Extreme decreases in oxygen levels may lead to more frequent fish kills. Warmer water also affects microbial processes, such as nitrogen fixation and denitrification in estuarine ecosystems.[58]

Increased temperatures, more intense storm events, and more frequent droughts will stress freshwater habitats, including streams, rivers, and ponds, and may lead to changes in species composition, especially for aquatic species dependent on specific timing and amount of available water. For example, the condition and function of vernal pools and coastal plain seasonal ponds may be affected by more intense winter storms followed by drought conditions and higher temperatures. The way species such as amphibians use these habitats may be affected. Changes in water temperature have important influences on aquatic ecosystem functions, such as reduced levels of dissolved oxygen and increased rates of biological processes. Warmer surface waters can promote algal blooms, including toxic blue-green algae, and lead to eutrophication of lakes, ponds, and streams. Increased precipitation increases the amount of organic material washing into lakes and streams, leading to higher concentrations of dissolved organic carbon (DOC), altering chemical and biological functions in the ecosystem.[59] Climate change impacts in freshwater ecosystems can also promote the establishment and expansion of invasive aquatic species.

8.4.7. Forest Ecosystems

As described in Section 8.1 above, this discussion of Delaware's forests includes upland forests and forested wetlands. Shifts in the range of forest species and composition of forest communities are likely to be triggered by changes in temperature. Some forest types are projected to expand their range as a result of temperature increases. Models projecting the future distribution of forest types in the northeastern United States show that oak-hickory forests are likely to increase at the expense of maple-beech-birch habitats. Loblolly pine (*Pinus taeda*) is common and widespread in Sussex County, but increased temperatures could allow it to expand its range northward. Forest composition and structure may be more critical to animal species responses than the presence or absence of any one plant.

Many factors will influence the rate and extent of changes in range and uncertainties about the ability of forest species to adapt to the relatively rapid pace of climate change.[60] Studies indicate that many tree species have a slower rate of migration that will limit their ability to keep pace with changes in temperature. For example, in a study of five eastern U.S. tree species, models suggest that these species are not likely to colonize more than 20 kilometers (approximately 12 miles) beyond their current boundary over the next 100 years. Slower migration rates are expected for species that decline in abundance toward the edge of their current boundaries.[61] In addition, the highly fragmented condition of forests in Delaware will present a barrier to migration for both plant and animal species.

Changes in air chemistry related to climate change are expected to affect forest health and productivity. Rising levels of atmospheric CO_2 and longer growing seasons are likely to increase productivity, but these gains may be offset by other factors, such as drought, pollution, and potential increases in pests and disease. Higher concentrations of CO_2 stimulate plant growth in some species more than others. For example, temperate forests have seen increases in woody vine species over the past several decades, a trend that can alter species composition and structure of forest habitats.[62] Increased CO_2 may also alter leaf chemistry, with potential consequences for herbivores in forest communities.[63]

Climate change is likely to cause changes to the cycling of nutrients in forest habitats. Some studies suggest that as climate warms, releases of CO_2 from the soil will increase as a result of increased soil respiration. This poses the possibility that forests could shift from serving as carbon sinks to being sources of carbon emissions.[64] Increased air temperatures are also associated with higher levels of ground-level ozone, which damages plant tissues and impairs photosynthesis.

Changes in precipitation will affect Delaware forests in direct and indirect ways. Increased frequency and/or duration of drought combined with increased air temperatures will lead to higher evapotranspiration and decreased soil moisture. These factors are likely to contribute to plant stress, resulting in decreased productivity and greater susceptibility to pests and diseases. High rainfall events will produce changes in forest wetlands by altering hydrologic patterns, and exacerbating flooding and erosion problems.

Pests, pathogens, and invasive plants are existing threats to forest habitats; the spread and severity of pest outbreaks will be influenced by precipitation and temperature changes related to climate change. Increases in winter temperatures, in particular, are likely to allow overwintering of insect pests that are currently kept in check by cold winters. For example, southern pine beetle (*Dendroctonus frontalis*) populations fluctuate in response to winter temperatures; the Delaware Forest Service reported that a high percentage of the overwintering population of the beetle in 2011 was reduced by unusually cold temperatures in the previous winters, a trend that could reverse following mild or warm winters.

Other pest species may be "winners" or "losers" under drier or wetter climate conditions. For example, wet spring weather increases the effectiveness of the fungus *Entomophaga maimaiga* in controlling gypsy moth (*Lymantria dispar*).[65] Some harmful forest pathogens may benefit from increases in temperature and precipitation. High rainfall conditions can increase spore production of fungal pathogens and facilitate their dispersal through rain splash and surface runoff. In addition, pathogens typically infest weakened or stressed host plants, therefore presenting a greater risk to forest trees suffering from drought-stress or other climate-related impacts.

Invasive plant species also pose an existing threat to forest habitats, and some studies indicate that certain aggressive, weedy species may increase under warmer and wetter climate conditions. Many invasive plant species can tolerate a wide range of temperature and precipitation, increasing their competitive advantage over some forest species with more specific tolerances. In addition, invasive plants often have characteristics that allow for long-distance dispersal, which allows rapid expansion into new areas as climatic conditions change.[66]

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Chapter 9 – Infrastructure Summary

Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3-4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- Energy demand for cooling is projected to increase by up to 130 percent by end of century, while energy demand for heating is projected to decrease by up to 40 percent by end of century (**Figure 9.1**).

Precipitation Changes

- Precipitation is projected to increase, particularly in winter (**Figure 9.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of

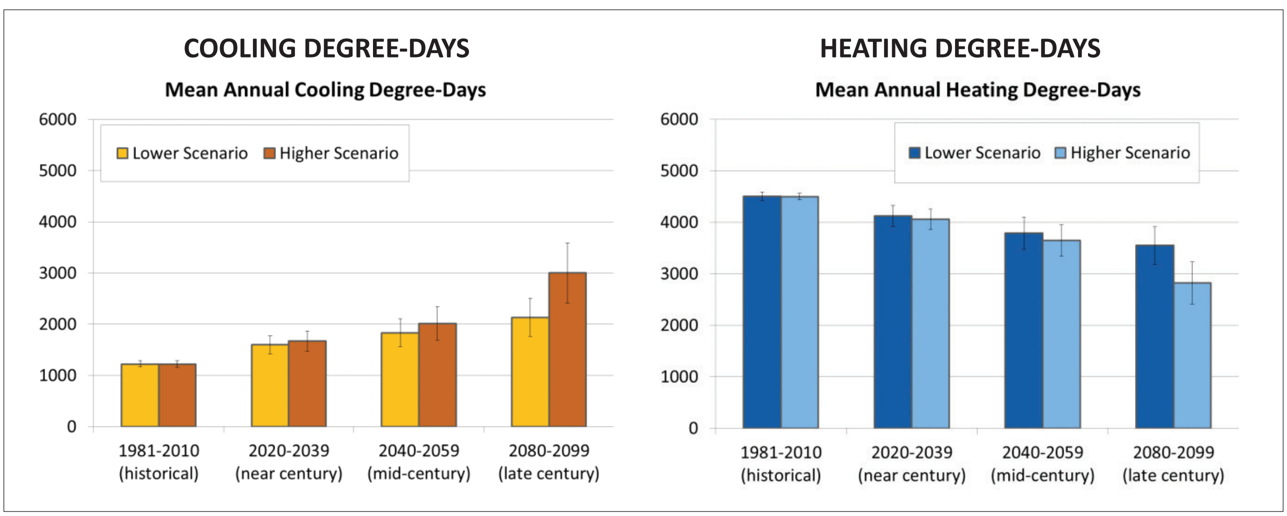

Figure 9.1. Cooling and heating degree-days provide a useful indicator of demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). This is calculated as the cumulative number of hours per year above (for cooling) or below (for heating) 65˚F. Source: Hayhoe et al. (2013).

heavy precipitation events, indicating an increase in precipitation intensity.

Potential Impacts to Infrastructure

- ***Extreme weather events*** can have direct and indirect impacts to the structural and operational use of infrastructure. Back-to-back storms or cascading events can lead to power outages and the shutdown of public transit. During intense storm events the higher volume and velocity of surface runoff can result in rapid erosion and scouring. This can undermine structural supports for roads, rail, bridges, and culverts, and other drainage structures. Many of Delaware's 48 regulated dams are located adjacent to or integrated into state-managed roads and bridges. In extreme rain events, dams may be vulnerable to damage or failure. Thus, roads or bridges located on top of, next to, or downstream from these structures are at risk of serious flooding or washout. Extreme weather events can also cause damage to natural infrastructure, such as wetlands and beaches, which may impair their ability to buffer inland areas.

- Changes in ***precipitation*** patterns may lead to a greater extent or frequency of flooding and increase the vulnerability of infrastructure in flood-prone areas. A potential shift toward more winter precipitation falling as rain instead of snow may alter the amount of snowpack in upstream portions of the Piedmont Basin. This may result in changes in the timing of spring thaw and shifts in seasonal flows and water levels that could increase flooding, particularly in urban areas of northern Delaware. Increased precipitation and associated flooding may increase the vulnerability of remediation sites and landfills associated with industrial facilities.

- ***Sea level rise*** poses potential impacts to natural and human-built infrastructure along Delaware's Atlantic and Delaware Bay coastlines. Roads and bridges throughout the state may be affected by sea level rise, particularly in the Inland Bays area. Delaware Bay beach communities may be vulnerable to more frequent tidal flooding of primary access roads and evacuation routes. The Port of Wilmington is a major facility that could be significantly affected. Public boat ramps and piers throughout coastal Delaware are also at risk for intermittent or chronic flooding as a result of sea level rise. Facilities located along the Delaware River and in the Inland Bays are vulnerable to inundation from sea level rise, and potential changes in salinity may affect industrial operations.

- ***Increasing temperatures*** and heat events are likely to affect transportation and energy infrastructure. Thermal stress or damage to energy infrastructure from heat-driven storms can impair electricity transmission. Higher air and water temperatures, or lack of available water for cooling, can affect operations and reduce electricity output. Increased heat can accelerate deterioration of the structure and surface of roads and bridges. These impacts may require increased maintenance and more frequent monitoring to prevent damage and ensure public safety.

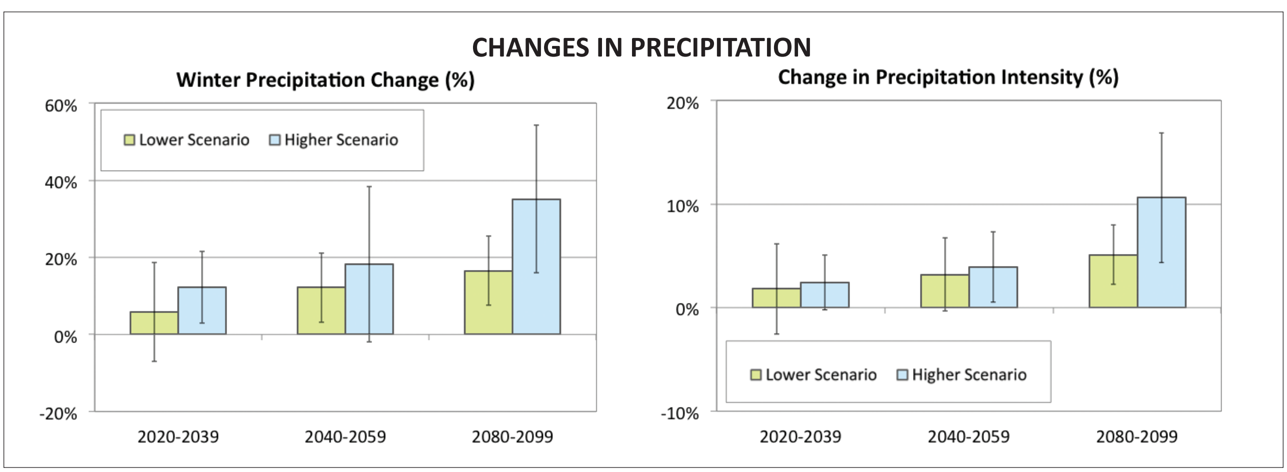

Figure 9.2. Precipitation increases are projected, primarily for winter and fall. Increasing precipitation intensity reflects projected increases in the frequency of heavy rainfall. Source: Hayhoe et al. (2013).

Chapter 9 Infrastructure

Chapter Contents

- Overview of Delaware's infrastructure, including natural and human-built infrastructure, with a focus on transportation and energy systems
- Summary of climate change impacts that pose challenges to infrastructure throughout the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to infrastructure (nonclimatic impacts to resources)
- Potential vulnerabilities to infrastructure in Delaware (based on current research and expert interviews – statewide scope)

In this chapter "infrastructure" is used to include both the human-built environment and the natural environment. Infrastructure is not defined solely as physical structures or facilities, but also in terms of the functions it serves. These functions, including "ecosystem services," are described and integrated into many sections in the Climate Change Impact Assessment. For example, Chapter 7, Agriculture, reflects the provisioning services of agricultural systems. In Chapter 8 on Ecosystems and Wildlife, many of the ecosystem functions described reflect regulating services, such as the water filtering function of wetlands. (See definitions of ecosystem services in Section 9.1.1. below.)

It is also important to consider that natural infrastructure and human-built infrastructure operate in integrated and interdependent ways. For example, natural infrastructure such as wetlands and forests can act as critical buffers to slow surface water runoff during storm events, thus reducing the impacts to human-built stormwater conveyance structures. Similarly, natural habitats perform biological functions that help to filter, absorb, or store pollutants. As ecosystems respond to climate change impacts, human-built infrastructure will be affected by changing environmental conditions as well.[2]

The human-built infrastructure discussed in this chapter focuses primarily on transportation and energy systems. Water infrastructure (water supply, distribution, treatment, wastewater, and stormwater systems) is discussed in Chapter 6, Water Resources.

9.1. Overview of Delaware's Infrastructure

9.1.1. Natural Infrastructure

An overview of Delaware's natural infrastructure would be incomplete without a brief discussion of the services that ecosystems provide, not only for the species and habitats they support, but for physical and biological functions on which human societies depend. Ecosystem services encompass a wide range of "benefits people obtain from ecosystems."[3] These benefits are discussed in this chapter to underscore the importance of the natural systems in supporting human needs.

Ecosystem services are defined by the Millennium Ecosystem Assessment and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change to include:

- *Regulating services* that moderate climate, floods, disease, wastes, and water quality, and
- *Provisioning services* that provide goods for human use and consumption, such as water and food.[4]

Delaware supports extensive natural habitats that serve a wide variety of ecosystem functions. In the context of infrastructure, many habitats provide regulating services that can support, or perform in place of, engineered systems and structures. The function or performance of habitat in providing ecosystem services depends on the type of habitat and its condition. Loss of habitat often results in loss of the ecosystem services. Degradation or fragmentation of habitat can result in reduced function. Under current conditions, many of Delaware's natural ecosystems are fragmented or impaired by a variety of stressors. Additional impacts from climate change could reduce or eliminate these habitats, or further affect their ability to provide ecosystem services.

Wetlands and Aquatic Ecosystems

Delaware's extensive wetland (both tidal and nontidal) and aquatic habitats provide many important functions that enhance and protect human communities and built infrastructure. In addition, these ecosystems provide cultural and aesthetic values for humans, as well as economic benefits related to tourism and recreation opportunities. Wetland types (both freshwater and saltwater) vary widely in vegetation type, hydrology, geographic location, and connectivity to other wetlands and other landforms (as described in Chapter 8, Ecosystems and Wildlife). Wetlands can serve a wide range of functions, as summarized in **Table 9.1**.

The condition of wetland habitat has a direct effect on its ecosystem function. A recent assessment of Delaware's wetlands from 1992 to 2007 concluded that between 40 and 65 percent of the state's wetlands provided high or moderate levels of ecosystem services.[6] Enhancement of wetland habitat, as well as protection from further habitat losses, is important for maintaining and improving the functional performance of wetlands.

Wetlands are also important for carbon storage; the benefit of carbon sequestration[a] in soils and vegetation can reduce or avoid carbon emissions into the atmosphere and thus helps to regulate climate. The varied ability of different types of wetlands to store carbon is being widely studied, and some research projects are attempting to develop measures for carbon storage in tidal wetlands and to evaluate factors affecting rates of carbon storage.[7]

a Carbon sequestration is the process by which atmospheric carbon dioxide is taken up by trees, grasses, and other plants through photosynthesis and stored as carbon in biomass (trunks, branches, foliage, and roots) and soils. The sink of carbon sequestration in forests and wood products helps to offset sources of carbon dioxide to the atmosphere, such as deforestation, forest fires, and fossil fuel emissions. (U.S. Forest Service, http://www.fs.fed.us/ecosystemservices/carbon.shtml)

Table 9.1. Wetland ecosystem services

Wetland Function	*Associated Ecosystem Services*
Surface water detention	Flood control
Streamflow maintenance	Water quality Water supply Recreation (e.g., boating, swimming)
Nutrient transformation	Water quality
Sediment and other particulate retention	Water quality
Coastal storm surge detention	Storm protection
Shoreline stabilization	Storm protection
Provision of fish/shellfish habitat	Commercial fishing and shellfish harvest Recreational fishing and shellfish harvest
Provision of habitat for waterfowl, water birds, and other wildlife	Hunting Wildlife viewing
Carbon storage	Climate stability

Source: Delaware Natural Resources and Environmental Control.[5]

Aquatic ecosystems, including freshwater ponds, lakes, streams, and rivers, provide many resource values for Delaware. Surface water is an important source of drinking water for the majority of the state's residents, and is essential for cooling water for electricity production and other industrial uses. In addition, waterways serve as transportation corridors, supporting the movement of goods in Delaware. The Delaware River is critical to the Port of Wilmington, and the Nanticoke River is an important waterway for transporting goods to and from the Chesapeake Bay.

Forests

Forest habitats are widely valued for a number of ecosystem services that support water supply and water quality. Forest habitats provide riparian (streamside) buffers for water filtration of surface runoff and thus prevent or reduce nutrient and sediment pollution from reaching waterways. Forests also protect groundwater quality and support groundwater recharge. Approximately one-fourth of Delaware's groundwater recharge areas are forested.[8] In addition, by slowing and regulating the infiltration of precipitation, forests also provide flood and stormwater control. In urban settings, trees and forest buffers can function as "green infrastructure" to help reduce the volume and velocity of stormwater flow and decrease the impact of flooding during storm events.

Forests also provide ecosystem services that benefit air quality and climate regulation. Forested wetlands are estimated to provide substantial carbon storage in both soils and aboveground biomass.[9] In addition, trees filter air through their leaves and can trap particulates, such as dust and ash, and absorb gaseous pollutants. Delaware supports an estimated 7.1 million urban trees that help remove hundreds of tons of nitrous oxide, sulfur dioxide, and ground-level ozone.[10] Trees and other vegetation also lower surface and air temperatures, reducing the heat island effect in urban areas. For example, during peak temperature periods, shaded surfaces may be up to 45˚F cooler than unshaded surfaces, a difference that can help reduce air temperatures by 2 to 9˚F. Even in suburban areas, landscapes with mature trees can be 4 to 6˚F cooler than suburbs without trees.[11] These climate regulation services can improve public health and reduce energy costs. In New Castle County, urban trees provide an estimated annual savings of more than $400,000 in residential building energy costs.[12]

Beaches and Dunes

The beaches and dunes along Delaware's bay and ocean shoreline function as the first line of defense against storm waves and tides. Wide beaches and healthy dunes serve as "shock absorbers" to distribute wave energy from coastal storms. As wave energy is expended by the movement and redistribution of sand along the shoreline, the impacts to coastal structures, such as homes, businesses, and roads, is greatly reduced. Large, vegetated dunes also serve as protection from wind and can reduce the impact of coastal flooding by buffering storm surge and storing water from heavy precipitation. Beaches and dunes provide value as buffers that protect buildings and infrastructure from storm and wave damage. On a larger scale, beaches and dunes that separate the Atlantic Ocean from the Inland Bays help protect inland tidal wetlands and aquatic ecosystems.

Economic Benefits of Natural Infrastructure

The benefits of natural infrastructure and the ecosystem services that they provide to human communities can be measured directly and indirectly. Studies of the economic value of ecosystem services have estimated the benefits provided by various habitat types. For example, Delaware's beaches draw nearly 5 million visitors each year, and access to public beaches represents a significant economic value to the region and the state.[13] (There are several recent reports on the economic value of Delaware resources; these are referenced in Chapter 1, Introduction, Section 1.2.)

A study of the Delaware Estuary watershed estimated the economic value of goods and services provided by various types of ecosystems, such as water filtration, flood reduction, and carbon storage. This analysis estimates that the value of goods and services derived from freshwater wetlands is more than $13,000 per acre per year. Similarly, the value of goods and services derived from saltwater wetlands is estimated at more than $7,000 per acre per year.[14] A similar study of the economic value of the Chesapeake Bay watershed in Delaware described ecosystem services such as air filtration, water filtration, recycling nutrients, soil conservation, pollination of crops and plants, climate regulation, carbon sequestration, flood and stormwater control, and hydrologic-cycle regulation. This analysis concluded that forests, freshwater wetlands, and farms provide the highest ecosystem values; for example, the value of goods and services derived from forests is estimated at approximately $14,000 per acre per year.[15]

One approach to valuing ecosystem services can be estimating the anticipated costs associated with the loss of those habitats that provide the services. An economic assessment conducted in 2011 of ecosystem services provided by wetlands in Delaware highlighted the value of wetland functions for carbon storage, water purification, flood protection, and wildlife protection. This study evaluated the economic impact of a continued decline in wetlands across the state over a 15-year time frame (2007 to 2022). The study estimated that a 1.2 percent decline in wetlands during that time frame would result in the loss of ecosystem services that would have significant social costs. For example, reduced carbon storage from loss of wetlands would lead to increased carbon emissions in the atmosphere; the social cost of the additional carbon emissions is estimated to be nearly $20 million (over 15 years). The study also evaluated the loss of water purification function provided by wetlands, resulting in increased municipal water treatment costs of more than $9.5 million (over 15 years).[16]

9.1.2. Human-Built Infrastructure

Delaware's human-built environment encompasses a wide array of structures that serve many functions for society. A comprehensive survey of the human-built environment is beyond the scope of this Assessment, but could include: homes, businesses, schools, public buildings, industrial facilities, and communication infrastructure. Note that water infrastructure is discussed in Chapter 6, Water Resources, and agricultural infrastructure is described in Chapter 7, Agriculture . This chapter focuses on two major elements of infrastructure – transportation and energy – that are integral to Delaware's economy, public safety, and quality of life.

Transportation Infrastructure

The Delaware Department of Transportation (DelDOT) maintains the vast majority (89 percent) of the 13,500 lane miles[b] of roads and highways in Delaware.[17] This represents nearly 9,000 miles of roadway measured by center line.[18]

The road transportation network includes interstate highways, expressways, major and minor arterials, and hundreds of miles of local roads. Major state highways include:

- State Route 1, a major north-south route from Interstate 95 near Newark to the Maryland state line in Sussex County. The coastal portion of SR 1 is a major access route to state beach parks and tourist facilities, including the 25-mile scenic coastal highway from Lewes to Fenwick Island.

- State Route 9 is a designated "Coastal Heritage and Scenic Byway" that runs 51 miles from the City of New Castle to south of Dover Air Force Base, mostly along the western shore of the Delaware River and Bay. It includes Reedy Point Bridge, which passes over the Chesapeake and Delaware (C & D) Canal and through communities such as Delaware City and Leipsic. SR 9 supports tourism-related traffic through its mostly rural corridor to many of the state's finest wildlife areas. In addition, truck traffic on SR 9 includes trucks serving the petrochemical complex near Delaware City and munitions trucks diverting around the City of Dover to reach Dover Air Force Base.

b Lane miles equal the length of roadway multiplied by the number of lanes; this measure reflects the increased capacity and maintenance needs of multilane roads.

- U.S. Highway 13, also known as the Du Pont Highway, is the longest stretch of highway in the state, running north-south from the Philadelphia Pike to the Maryland state line near Salisbury. The federal highway is a major linkage for towns in all three counties: from Claymont, Wilmington, and Odessa in New Castle County; through Smyrna, Dover, Camden, and Harrington in Kent County; and to Laurel, Seaford, and Delmar in Sussex County.

- Interstate 95, a federal highway, is a major east-west corridor through northern New Castle County. Annual average daily traffic on I-95 on this stretch is estimated at more than 168,000 vehicles. In addition, I-495 carries an annual average daily traffic count of nearly 76,000 vehicles.

The Delaware system of highways and roads includes designated evacuation routes that provide critical linkages during emergencies such as major tropical storms and hurricanes. There is an estimated 1,185 miles of roads serving as evacuation routes in Delaware. Some of these evacuation routes serve small coastal communities that have only one road available for ingress and egress; coastal flooding or other disruptions to the function of these roads can leave coastal residents isolated. Some urban areas are also challenged by flooding during major storm events, affecting connector roads that may cut off access to evacuation routes.

DelDOT maintains 1,576 of the 1,660 bridges in Delaware.[19] The other 84 bridges are the responsibility of the Delaware River and Bay Authority (DRBA), municipalities, railroads, and private owners. Two of the largest state-managed bridges are the Chesapeake & Delaware (C & D) Canal Bridge and the Indian River Inlet Bridge. The C & D Canal Bridge on State Route 1 (also known as the William V. Roth, Jr. Bridge) supports a daily traffic count of more than 70,000 vehicles. The Indian River Inlet Bridge in southern Delaware is a critical component of State Route 1 in Sussex County; the newly reconstructed bridge opened in January 2012. The Delaware Memorial twin suspension bridges carry more than 34 million cars annually between Delaware and New Jersey. The twin spans are managed by the Delaware River and Bay Authority (DRBA), a bistate government agency of the states of New Jersey and Delaware established by interstate compact in 1961.

The DRBA also operates the Cape May-Lewes Ferry between Cape May, New Jersey, and Lewes, Delaware, and the Three Forts Ferry Crossing (passenger ferry between Fort DuPont, Fort Delaware, and Fort Mott, NJ). The Cape May-Lewes Ferry provides passenger and car transport across Delaware Bay. Summer service averages 11 to 17 trips per day; annual ridership in 2010 totaled nearly 845,000 passengers and nearly 300,000 vehicles.[20]

Public transit in Delaware includes statewide bus and paratransit services and regional rail systems. The state's public bus system, DART First State, is managed by the Delaware Transit Corporation, a subsidiary of DelDOT. The agency operates more than 60 fixed bus routes with an annual ridership of more than 9 million (ridership represents the number of passenger trips). DART Paratransit offers door-to-door transit service for disabled riders; regular fixed-route buses are also wheelchair-accessible and equipped with bike racks.

Public transit in Delaware is also served by regional railroad systems, concentrated in northern New Castle County. Passenger rail service is provided by Amtrak, the Southeastern Pennsylvania Transportation Authority (SEPTA), and the Wilmington & Western Railroad.

- Amtrak operates intercity passenger rail service, with up an average of 80 trains daily serving the Wilmington train station and two trains daily serving the Newark Station, providing more than 700,000 passenger trips annually to and from Delaware.

- SEPTA's Wilmington-Newark line provides commuter train service to four Delaware stations, with 35 trains each weekday to Claymont and Wilmington, and 17 trains each weekday to Churchman's Crossing and Newark.

SEPTA service in Delaware is funded by the Delaware Transit Corporation and supports a ridership of more than one million each year.

- The Wilmington & Western Railroad is a historic railroad that offers tourist rail trips in the Red Clay Valley between Greenbank and Hockessin.

Freight railway in Delaware is provided by two large, long-distance railroads – CSX Transportation and Norfolk Southern Railway – and four short-line rail services. Approximately two-thirds of inbound freight consists of coal, nonmetallic minerals, and chemicals; nearly two-thirds of outbound freight consists of nonmetallic minerals, transportation equipment, and chemicals. The railway systems operated by CSX and Norfolk Southern connect regional and national transportation networks with the Port of Wilmington and other parts of the state, including shipping coal to southern Delaware for power generation. Short-line rail service is provided by Delaware Coast Line Railroad in Sussex County; East Penn Railroad with an interchange with CSX Transportation in Elsmere Junction; and Maryland & Delaware Railroad Company with rail service to Townsend, Seaford, and Frankford.

Air transportation is available through several public airports in Wilmington, Dover, and Georgetown. Delaware's public airports provide mainly private, local, and recreational service; most commercial air travelers use the Philadelphia and Baltimore international airports. The DRBA operates several aviation facilities in Delaware: New Castle Airport (Wilmington), Delaware Airpark (Dover), and the Civil Air Terminal at Dover Air Force Base. Sussex County operates the Sussex County Airport.

Dover Air Force Base, in Kent County, is the largest aerial port facility on the East Coast and serves as an important facility for overseas military operations. A joint use agreement between the base and the Department of Transportation allows private aircraft to use the adjacent DAF Civil Air Terminal.

The Port of Wilmington is a full-service deepwater port and marine terminal located at the confluence of the Delaware and Christina Rivers, 65 miles from the mouth of Delaware Bay. The port is owned and operated by the Diamond State Port Corporation, a corporate entity of the State of Delaware. It supports significant economic activity, with approximately 400 vessel calls and shipments of more than four million tons of cargo each year.[21] The port facility covers approximately 216 acres and includes seven deep-water cargo berths, a floating berth, and a petroleum berth along the Christina River. In addition, there are more than 1,000 acres surrounding the port that include transportation, storage, and processing infrastructure to support port activities.[22]

The Port of Wilmington includes the largest dockside cold-storage facility in the United States, with 800,000 square feet of cold storage in six warehouses; this cold-storage capacity makes Wilmington the top port in North America for imports of fresh fruit, bananas, and juice concentrate. An auto and roll-on-roll-off (RoRo) berth is located on the Delaware River; the port is an important auto export facility for shipping U.S. cars abroad. The port includes 33 acres of open space for RoRo containers, steel, lumber, and other bulk cargo, as well as 250,000 square feet of dry warehouse storage. Wilmington is also a major port and distribution center for liquid bulk petroleum products, with more than one million tons of liquid petroleum transported into the port by tanker vessels and barges.[23]

Energy Infrastructure

An overview of Delaware's energy infrastructure includes a summary of production, transmission, and distribution systems that transfer electricity, natural gas, and oil to homes and businesses throughout the state. Delaware's energy production relies greatly on imported energy fuels, as the state does not produce coal, petroleum, or natural gas. These fossil fuels are transported into Delaware by ship, train, and truck to refineries, industries, and power plants. Delaware uses renewable energy sources with some biomass, solar, and wind facilities, although these represent a small portion of energy usage in the state.

Electricity in Delaware includes both generators (private, independent power producers) and distributors (utilities that manage transmission and delivery infrastructure). Larger electricity generation facilities provide base load (continual power production) and others operate during peak demand periods. (Megawatts, MW, shown below indicate total net summer capacity, according to the Energy Information Administration.) Primary energy sources used in Delaware for electricity production are natural gas and coal. As of October 2013, electricity generators in Delaware include the following:[24]

- Calpine Mid-Atlantic Generation, LLC, with five power plant facilities, including the Hay Road facility (1,130 MW) and Edge Moor facility (723 MW), both of which use natural gas. Calpine owns three peaking plants that use petroleum: Delaware City (23 MW), Christiana Energy Center (53 MW) and West Energy Center (20 MW).

- NRG Energy operates the Indian River Generating Station (795 MW), which uses coal. (This plant has ceased operation of two of its four units and another unit is scheduled to shut down in 2013.) NRG also operates the NRG Energy Center in Dover (100 MW). The power plant was converted from the last coal-fired generating unit to combined cycle natural gas in 2013.

- NAES Corporation operates natural gas–fired power plants in Dover, including the McKee Run (136 MW) and Van Sant Station (39 MW) facilities.

- Delaware Municipal Electric Corporation owns the natural gas–fired Sam Beasley Generation Station in Smyrna (98 MW).

- AMERESCO operates two biomass-fueled facilities using landfill gas in Georgetown (5 MW) and Sandtown (3 MW).

- SunPower Corporation and White Oak Solar Energy operate the Dover Sun Park (10 MW), a solar power facility that opened in 2011.

- PSEG Milford Solar Farm (15 MW), a new solar power facility, opened in 2013.

- University of Delaware operates a wind turbine (First State Marine Wind) (2 MW) at its Hugh R. Sharp Campus in Lewes; the turbine began operation in 2010.

- Delmarva Power operates the Bloom Energy Facility (30 MW), a fuel cell producer of electricity, in Newark.

Distribution of electricity to homes and businesses is provided by Delmarva Power, the Delaware Electric Cooperative, and the Delaware Municipal Electric Corporation, which represents municipal electric utilities, including Clayton, Dover, Lewes, Middletown, Milford, Newark, Seaford, Smyrna, and the City of New Castle. Transmission and distribution of electricity requires the operation and maintenance of extensive infrastructure to transfer transmission-level voltages from substations through hundreds of miles of lower-voltage electric lines, transformers, and electric wires to connect to end users. More than one-fourth of Delaware households use electricity as their primary energy source for home heating.[25]

Natural gas is used widely throughout Delaware and is distributed through two regulated utilities: Delmarva Power serves New Castle County and Chesapeake Utilities Corporation serves Kent, Sussex, and southern New Castle Counties. Two interstate pipeline systems supply natural gas through more than 300 miles of underground pipes from Pennsylvania and Maryland to Delaware. Industry and electricity generators are the largest consumers of natural gas in the state; in addition, more than one-third of Delaware households use natural gas for home heating.

Petroleum products are processed in Delaware's one refinery facility, the Delaware City Refinery, located in New Castle County. Operated by the PBF Holding Company, LLC, and the Delaware City Refining Company, the plant refines crude oil into automobile gasoline, home heating oil, and other petroleum products. Crude oil supplies are transported to Delaware through the Port of

Wilmington. Approximately one-fifth of Delaware households use heating oil as their primary energy source for home heating.

9.2. Climate Change Impacts to Infrastructure in the United States

Studies on the potential impacts of climate change to infrastructure often focus on the built environment, particularly with regard to transportation, energy, and water systems. The discussion of impacts to infrastructure is not limited to the structures themselves, but also to the services those structures provide. These services are essential to the health, safety, and economic productivity of human communities. For cross-reference, please note that climate change impacts to water infrastructure are described in Chapter 6, Water Resources . Also, impacts to natural systems that provide important ecosystem functions, such as water resources, wetlands, and forests, are described further in Chapter 8, Ecosystems and Wildlife.

9.2.1. Interdependent Systems

Infrastructure systems are highly interactive and interdependent. For example, water systems require energy for pumping, distribution, and water treatment. Transportation systems are necessary for energy production by moving raw materials to refineries and power plants, and for transporting refined energy products to end users. Infrastructure sectors, such as transportation and energy, are often planned for and managed individually. Yet in response to significant changes, such as extreme weather events, infrastructure systems are closely linked and interdependent. Disruptions that affect one infrastructure system can have a cascading effect on other systems, leading to increased vulnerability and, in some cases, unexpected impacts. For example, direct damage from Hurricane Irene in 2011 to the City of Baltimore included flooding and wind-damaged trees, but also contributed to power outages that led to sewage spills that continued for days after the storm ended. A widely cited example of the cascading effect of an extreme weather event is Hurricane Katrina in 2005. The indirect and long-lasting "ripple" effects of this disaster included a reduction in oil production, leading to a nationwide spike in gasoline prices and disruption of navigation on the Mississippi River that impeded grain shipments from reaching key ports in the Gulf vital for export.[26]

The wide-ranging, related impacts of extreme weather events reach individuals and businesses in many ways. Transportation impacts can prevent employees from getting to work, and thus cause them to lose wages. Power outages may close businesses for days, or cut off supplies and materials to keep businesses from operating at full capacity. For example, shrimp harvest in the Gulf of Mexico supplies stores and restaurants throughout the country. When severe weather disrupts the shrimp fishery or the transportation network that moves fresh shrimp to markets across the country, a "ripple effect" occurs throughout a larger region. Although many economic assessments have been made of natural disasters in the United States, it is recognized that the full scope of costs exceeds the direct damage to infrastructure.

Regional and local impacts to infrastructure vary, depending on the geographic patterns of land use and population density. For example, climate change impacts to rural areas, such as flooding of access roads, may affect relatively few people and businesses, but those who are affected may literally be cut off from emergency services or supplies for extended periods of time. Similarly, many coastal communities may be unable to access evacuation routes in extreme events. Urban areas are critical hubs for infrastructure systems and services due to their large populations and concentrations of economic and social activity. Urban infrastructure is highly integrated and provides essential functions to support people and businesses, both within the city and those who are passing through. Many U.S. cities are located in vulnerable locations on coasts or rivers. As a result, disruptions to urban infrastructure have significant impacts to the safety, mobility, and productivity of thousands of people.

9.2.2. Transportation Infrastructure

Transportation infrastructure includes human-built structures related to land transport (highways, roads, bridges, tunnels, and railroads), air transport (airports, runways, and related ground facilities), and marine transportation (ports, harbors, terminals, and docking infrastructure). Marine transport also relies on the natural infrastructure of rivers and waterways that provide the physical pathways for shipping and barge passage. Climate change impacts can affect transportation operations as well as infrastructure, as summarized in **Table 9.2** and discussed briefly below.

Transportation infrastructure can be affected directly and indirectly by changes in temperature, precipitation, extreme weather events, and sea level rise. All modes of transportation can be sensitive to weather events, but are most vulnerable to changes in extreme conditions.[28] Damage or disruption to transportation systems due to climate change impacts can affect public safety and economic activity across a wide area. For example, an extreme rain event in 1996 caused extensive flooding in Chicago and its surrounding suburbs, preventing commuters from reaching the city for up to 3 days. More than 300 freight trains were delayed or re-routed from Chicago, which serves as a major U.S. rail hub for freight transportation.[29]

The location of transportation infrastructure is also a factor in the degree of vulnerability to climate change impacts. Coastal areas are already subject to the effects of hurricanes and coastal storms; these impacts, along with sea level rise, are projected to increase over the next century. In addition, coastal regions are under significant development pressure. Nationwide, more than half of the population resides within a coastal watershed, and population density in coastal counties is much higher than in inland counties. Coastal areas are also important gateways for economic activity, particularly with major ports that connect freight shipping to rail and trucking networks.[30]

Temperature Impacts

Increasing temperatures and extended periods of extreme heat have direct effects on paved surfaces, including highways and airport runways. Extended periods of heat over 90°F can soften asphalt and result in buckling of roadways and rutting from vehicle traffic. Sustained high temperatures can also cause thermal expansion of road and bridge supports, affecting bridge operations. Higher temperatures will also increase the need for refrigeration in trucking and shipping, thus raising costs and energy demand. High heat events can also delay transportation construction and maintenance projects if work stoppages are required to avoid health risks to workers.

Table 9.2. Potential climate change impacts to transportation in the United States

Climate Change Impact	*Potential Impacts to Operations*	*Potential Impacts to Infrastructure*
Increased temperatures and increase in extreme heat events	• Airports: affects aircraft lift, reduced load capacity • Roads: limits on construction activity due to health and safety concerns	• Roads and air runways: thermal expansion of paved surfaces causing buckling and rutting • Bridges: thermal expansion of bridge joints and structure • Railroads: track deformities
Changes in precipitation and extreme weather events	• Roads: traffic disruptions and delays • Roads: increasing emergency evacuations, flooding of evacuation routes • Roads/railroads: damage or clean-up from storm debris • Airports: delays and cancellations	• Roads: damage to roads and culverts from flooding • Bridges: damage to support structures, threat to deck stability • Railroad: damage to track and support structures • Ports and harbors: impacts from wave damage
Sea level rise	• Roads: flooding of access roads and evacuation routes • Waterways: higher water levels may affect bridge clearance • Ports: changes in navigation channels	• Roads/railroads: increased coastal flooding, damage to support structures • Ports: decks and equipment may require retrofits to adapt to higher water levels • Harbors: impairments to inland waterways

Source: Adapted from National Research Council (2008).[27]

Railroad infrastructure is also affected by extreme heat. Air temperatures above 100˚F can cause deformities in rail tracks, such as buckling, kinks, and misalignments, that can result in train derailments. Orientation of tracks may increase vulnerability to high heat, as the sides of east-west rail tracks heat at greater rates than north-south tracks. Heat conditions may also affect rail operations, requiring lower speeds, shorter trains, or lighter loads to reduce track stress.[31]

Increasing heat can affect air transportation facilities and operations. Runway pavements may be affected as are roads and highways, with buckling and rutting of softened surfaces. Higher temperatures can alter operational capacity, because heat makes air less dense and reduces aircraft lift, particularly at high altitudes. As a result, planes need longer runways and/or reduced weight to take off.[32]

Warmer winter temperatures may result in some benefits for transportation, such as reduced snow and ice removal costs for highways and airports; reduced environmental impacts from the use of salt or chemicals on roads and bridges; fewer impacts to ports and harbors related to ice accumulation on vessels and docks; and reduced need for de-icing planes.[33]

Precipitation and Storm Impacts

Increasing frequency and intensity of rain events is likely to result in more flooding, which will affect roads, airport runways, and other transportation facilities in low-lying areas. Land transportation infrastructure often includes large areas of impervious, paved surfaces, which magnify the effects of storm runoff. The quantity and velocity of runoff in rain events can damage or accelerate the deterioration of roads, bridges, and railroad tracks. Increased flooding can also lead to increased subsidence, erosion of embankments, and scouring of bridge supports.[34]

Extreme weather events and stronger tropical storms present several hazards to transportation infrastructure in addition to heavy rainfall. High winds can cause extensive damage and leave debris on roads and rail lines. Wind-driven storm surge also has huge impacts on coastal infrastructure. In ports and harbors, storm surge and wave action can damage or destroy cranes, docks, and storage facilities. Freight operations can be significantly affected when transportation connections are interrupted, such as barge transport on water, and freight transfers to rail and trucking systems.[35] Air transport is likely to be delayed, cancelled, or re-routed, causing interruptions to passenger and freight movement.

Storms and flooding may also lead to more frequent and extensive emergency evacuations, especially in coastal areas. This can pose a significant threat to public safety if the evacuation routes are also affected by storm damage or flooding. Evacuations associated with hurricanes can be costly, too; losses in tourism, commerce, and general productivity can exceed $1 million per mile of coastline, according to one study. Nationally, floods and hurricanes are among the most frequent incidents prompting evacuations.[36]

Sea Level Rise Impacts

Sea level rise is likely to present significant long-term impacts to coastal transportation infrastructure. Inundation and tidal flooding of even a small portion of the coastline can lead to disruptions in transportation networks. For example, a port facility may be functional and accessible from the water, but if access roads or railways are affected, the port may be forced to reduce operations or shut down.[37] As sea level rises, dock levels may require retrofitting to function properly with dock cranes and other equipment.[38]

Sea level rise may have impacts to a range of transportation operations. Higher water levels could decrease clearance under bridges, affecting marine transport in harbor entrances and canals.[39] Changes in water levels and river flows may alter navigation channels due to changes in sedimentation rates and shifting locations of shoals. Transportation along inland waterways may also be affected by sea level rise, particularly where barrier islands are modified by increased erosion.

9.2.3. Energy Infrastructure

Across the United States, energy infrastructure includes a range of systems and facilities for producing and distributing energy in various forms:

- Oil and gas production involves structures for exploration and extraction (drilling equipment), processing (refinery facilities), storage (tanks), and distribution (pipelines).

- Thermal electric production includes power generation facilities that use various energy sources –coal, natural gas, nuclear energy, and petroleum – and infrastructure for electricity distribution networks (power lines, substations, and transformers).

- Renewable energy production includes hydroelectric facilities (dams, turbines, and generators), photovoltaic structures, wind turbines, geothermal energy, and distribution infrastructure to connect them to the electrical grid.

- Bioenergy sources require several stages for production: growing and harvesting feedstock (e.g., corn, woody debris); chemical processing facilities to produce ethanol or biodiesel; and infrastructure to integrate biofuels with other energy sources, such as mixing ethanol with gasoline, or using biomass for electricity generation.[40]

Climate change impacts can affect energy operations and infrastructure, as summarized in **Table 9.3** and discussed below.

Energy production and distribution can be affected directly and indirectly by changes in temperature, precipitation, extreme weather events, and sea level rise. The location of energy facilities is an important factor in the degree of vulnerability to climate change impacts. Oil and gas operations in Alaska, for example, are subject to impacts from changes in the permafrost layer supporting structures, roads, and pipelines. Coastal and off-shore oil and gas development are vulnerable to sea level rise, increasing storm intensity, and changes in ocean acidity related to increased levels of atmospheric carbon dioxide (CO_2).[41]

Climate change impacts on water availability will have significant effects on energy production. Power plants require large amounts of water and are sensitive to fluctuations in water supply. Regional water shortages, due to increasing temperatures and more frequent droughts, are likely to affect electricity production in many regions. In some areas, changes in seasonal water availability will alter the timing and capacity of hydroelectric power generation; in other areas,

Table 9.3. Potential climate change impacts to energy systems in the United States

Climate Change Impact	*Potential Impacts to Operations (Production and Refining)*	*Potential Impacts to Infrastructure (Transport, Terminals, and Pipelines)*
Increased temperatures and increase in extreme heat events	• Reduced efficiency of thermal electricity production • Regional impacts to energy production due to permafrost melt, shorter winter season (Arctic) • Increased evaporation in surface reservoirs, affecting water availability for hydroelectric energy production	• Damage or disruption to energy distribution systems (e.g., pipelines, electric lines) • Damage to pipelines and structures from melting permafrost (Arctic) • Changes to bioenergy feedstock production
Changes in precipitation and extreme weather events	• Disruptions in energy production and distribution from storm events • Reductions in power output from decreased water availability • Impacts to hydroelectric energy production from changes in amount or timing of precipitation • Coastal and offshore oil production disruption and damage to drilling infrastructure	• Damage to infrastructure (e.g., pipelines, electric lines) • Flood damage to roads and rails, disrupting transport of coal to power plants
Sea level rise	• Disruption to distribution of energy due to sea level inundation and coastal flooding	• Damage to infrastructure from inundation or coastal flooding of power plants, refineries, and pipelines

changes in water levels and temperatures will affect the efficiency of power plant cooling.[42]

Climate changes will also affect energy demands. Rising temperatures will increase electricity demand for cooling in most regions during peak periods (defined as a period of sustained demand for electricity at higher than average levels). For example, U.S. studies estimate that for every 1.8˚F increase in temperature, demand for cooling energy increases 5 to 20 percent. At the same time, demands for winter heating will likely decrease, which can affect demand for natural gas and fuel oil, with less effect on electricity use. Increasing energy demands are compounded by existing trends, such as demographic shifts of the U.S. population to the south (with higher air conditioning demand) and an increase in square footage per person, requiring additional space heating and cooling.[43]

Temperature Impacts

Thermal power plants will be affected by increasing air and water temperatures, as higher temperatures reduce the efficiency of cooling and can lead to lower power outputs. High heat events can also affect energy distribution systems, such as the failure of electric power transformers during heat waves, causing disruption of electricity supply.[44] Warmer water temperatures also have direct impacts on energy production. For example, regulatory constraints may limit the intake of cooling water from rivers, or may restrict the amount of water discharge from power plant cooling systems.[45]

Regional impacts will be greater in some energy production areas already experiencing changing conditions, such as the oil and gas industries on Alaska's North Slope. Temperatures in higher latitudes have been rising at a faster rate than in mid-latitudes, affecting the Arctic region with shorter winter seasons and thawing of permafrost. Both of these effects cause structural and operational problems for pipelines, airfields, and coastal structures associated with energy production.[46]

Increasing temperatures and rising levels of atmospheric CO_2 will affect bioenergy production, with regionally variable impacts to feedstock crops. For example, current U.S. production of ethanol depends largely on corn, which is vulnerable to high heat and drought conditions in the Midwest. However, future bioenergy fuels may rely more on a range of woody materials, which could benefit from changing climate conditions.[47] In addition, higher temperatures will likely lead to increased demand for irrigation, which affects water supply as well as energy consumption.

Higher temperatures are likely to affect hydroelectric energy, particularly in the western United States. With rising temperatures and more frequent droughts, evaporation of water from surface reservoirs will reduce water availability for hydroelectric power.

Precipitation and Storm Impacts

Extreme weather events have direct and indirect impacts on energy infrastructure. Hurricanes, in particular, have had devastating effects on U.S. oil and gas production in recent years. In 2005, direct losses to the energy industry from hurricanes were estimated at $15 billion. Hurricanes Katrina and Rita closed many oil and gas pipelines and stalled nearly 20 percent of U.S. refinery production.[48]

Changes in precipitation that lead to reduced water availability will have negative impacts for all types of energy production (with the possible exception of solar and wind energy). As described above, large quantities of water are necessary for thermoelectric power production, oil and gas development, and generation of hydroelectric power. In areas with declining water supplies, existing power plants may see reduced capacity and siting of new facilities may be limited.[49]

Increased frequency and intensity of heavy precipitation will result in flooding that can damage energy infrastructure, such as pipelines and power lines, resulting in power outages. In addition, storm events and flooding can disrupt transportation of fuels for energy production. For example, nearly two-thirds of the coal used in U.S.

power plants is transported by rail; where railroad lines follow rivers, as in the Appalachian region, flooding can wash out rail beds.

Hydroelectric power is affected when the amount or timing of precipitation and runoff is altered. In regions with declining precipitation and lower river flows, hydroelectric production will likely be reduced. In addition, a shift toward more precipitation falling as rain instead of snow in some regions will reduce the amount of river flow in late spring and summer, when spring thaw would normally sustain or increase river flows.[50]

Sea Level Rise Impacts

Energy production and distribution facilities are at risk for the direct and indirect effects of sea level rise. Power plants, refineries, and oil and gas pipelines may suffer equipment damage from saltwater inundation or coastal flooding from storm surge. The potential costs of repairing, retrofitting, or relocating coastal energy facilities may have a significant impact on energy prices.[51] In addition, distribution of energy may be disrupted by impacts to roads and railways due to sea level inundation and coastal flooding.

9.3. External Stressors

Climate change is one of many stressors that can affect natural and human-built infrastructure. Natural habitats are already challenged by a number of stressors, including habitat loss, altered hydrology, and other impacts that may be magnified or exacerbated by climate change. Human-built infrastructure is also subject to existing conditions and trends that affect the function and capacity of critical systems that provide transportation, energy, water, and communication services.

Population growth drives land development, which, in turn, requires infrastructure to support the growing population. Future development is a fundamental component of planning for long-range transportation and energy infrastructure needs. The increasing demand for transportation and energy services involves both a need for greater overall capacity and also greater geographic extent. Infrastructure must expand to areas of new growth while at the same time meeting the needs of densely populated urban areas. Delaware's population is projected to exceed one million by 2030, a 35 percent increase from 2000.[52]

Population growth creates additional demand on the transportation system to support both passenger and freight travel. Limitations of federal and state funding for road construction and repair will challenge transportation managers' ability to maintain existing roads while also adding new capacity. Congestion on heavily used roads and highways is an existing problem that is likely to worsen as population grows. Congestion and traffic demands are also affected by driving behavior, as well as the total number of drivers. When people drive more, the per capita measure of vehicle miles traveled (VMT) increases and higher emissions are generated. The United States has a significantly higher average VMT than does Europe or Canada, although this has declined since the economic downturn in 2007.[53] In Delaware, average VMT more than doubled between 1980 and 2005. However, the state's average VMT has declined in recent years, in spite of the increasing number of cars registered in the state.[54]

Population growth also drives increasing demand for energy in homes, businesses, and industries. Per capita energy consumption in the United States has been declining slowly over the past 25 years.[55] However, while there are reductions in energy use in some sectors due to technological efficiencies, other sectors may experience higher energy demands.

Aging infrastructure can add to costs and challenges in maintaining reliable, safe infrastructure. In many eastern U.S. cities, urban roads and bridges are subject to a greater volume of traffic than the 20th century demand for which they were designed. Some structures may be reaching the end of their functional lifespan and in need of replacement; other structures have been modified or expanded to accommodate increasing use. Most bridges are built to last roughly 50 years; of the 600,000 bridges in the United States today, the average age is 43 years. A 2008 survey of

U.S. bridges estimated that one in three urban bridges may be considered structurally deficient or functionally obsolete.[56]

Across the United States, infrastructure for energy transmission and distribution has not kept pace with new generation facilities. The American Society of Civil Engineers estimates that electricity demand has increased by approximately 25 percent since 1990, while construction of new transmission facilities has declined or been stagnant. Their report on U.S. infrastructure also identifies operational problems with maintaining voltage levels, as well as transmission constraints or "bottlenecks," that can lead to increasing costs and/or declining reliability in the energy system.[57]

Land use changes that accompany population growth have direct and indirect effects on infrastructure. Development of homes, businesses, and roads increases impervious surface area, such as buildings, concrete, and pavement. Impervious surfaces alter natural hydrology, resulting in higher volumes of stormwater runoff, increased erosion, and more frequent flooding. These impacts can increase the risk of damage or impairment of infrastructure components, such as bridge supports and poles for electric lines, and increase maintenance requirements and costs.

Land use changes have both environmental and societal effects on infrastructure. Shifts in growth patterns have consequences for planning and expanding services to new areas. For example, development spreading out to rural regions stresses the physical condition and capacity of local roads; in addition, safety problems can result when increased car traffic is sharing roadways with farming equipment.

9.4. Potential Impacts of Climate Change to Delaware's Infrastructure

The potential vulnerabilities of Delaware's infrastructure to climate change impacts can impair or disrupt the functions that help protect public health and safety, support economic activity, and enhance quality of life in our communities. As discussed above, infrastructure systems are highly interdependent; impacts to one component can affect other systems either directly or indirectly. In addition, natural environments provide ecosystem services that may be integrated with human-built infrastructure; therefore, impacts to ecosystem conditions can also affect infrastructure functions. The following summary describes some of the vulnerabilities that may affect all types of natural and human-built infrastructure in Delaware.

9.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- Energy demand for cooling is projected to increase by up to 130 percent by end of century, while energy demand for heating is projected to decrease by up to 40 percent by end of century (**Figure 9.1**).

Precipitation Changes

- Precipitation is projected to increase, particularly in winter (**Figure 9.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 9.2**).

9.4.2. Vulnerabilities to Impacts

Infrastructure and population density are not distributed equally across the state. Northern Delaware is a highly urbanized, densely populated region with a concentration of transportation, energy, and industrial facilities, including the Port of Wilmington, the I-95 corridor, and the majority of Delaware's petrochemical industry sites. These highly networked infrastructure systems can, on the one hand, provide some redundancy so that when one component fails, other components in the system can provide alternative or back-up function. On the other hand, when extreme events occur, a cascading effect can amplify the impacts to any part of the local infrastructure systems. In addition, Delaware's major infrastructure systems are part of larger, regional networks. For example, many of the state's industrial facilities depend on electrical distribution from neighboring states.

Central and southern Delaware represent a different landscape pattern, with lower-density communities connected by a north-south corridor of transportation and energy infrastructure. This geographic pattern presents a structure of a "main line" with "trunk lines" connecting to communities on the coast and to the rural communities in the western part of the state. As a result, services to the east or west of this north-south corridor can be affected by bottlenecks or disruptions in the system, so that homes and businesses farthest from the main line can be isolated. This vulnerability is evident in coastal communities that rely on a single road for ingress and egress.

Delaware's Atlantic coast and Inland Bays region supports a number of large communities that experience huge increases in summer population. Both residents and visitors in coastal regions are vulnerable to increased exposure to coastal storms and coastal flooding. In response to Hurricane Irene in 2011 and Hurricane Sandy in 2012, mandatory evacuations were required for all coastal communities in Delaware. This affected hundreds of residents and visitors in Sussex County within three-quarters of a mile of major waterways in Rehoboth Bay, Indian River Bay, Little Assawoman Bay, and Pepper Creek. In Kent County the mandatory evacuation affected areas within three-quarter of a mile of Delaware Bay, including Woodland Beach, Pickering Beach, Kitts Hummock, Bowers Beach, South Bowers Beach, and Big Stone Beach. New Castle County residents were also required to evacuate portions of Wilmington, New Castle, Delaware City, and areas south of the C & D Canal east of Route 9 including Port Penn, Augustine Beach, and Bayview Beach. Although emergency evacuations of this magnitude are uncommon, the dependence on infrastructure illustrates the potential vulnerability to coastal residents from increasing storms and flooding events.

Impacts from climate change are experienced differently by different populations of Delaware residents. Age, income, and transit-dependence are several factors that can increase vulnerability to climate change impacts that affect infrastructure. Older adults may have limited mobility or physical disabilities that make responding to extreme weather events more challenging. Senior citizens in retirement and coastal communities can be vulnerable in emergency situations, such

Road Culverts – Upgrading Aging Infrastructure

Culverts are widely used to direct water away from roads, either for stream crossings or runoff management, to help reduce roadway flooding and help preserve the road bed from erosion. In many states with aging infrastructure, road culverts were not designed to handle the increasing volume of streamflows and surface runoff that can occur in extreme weather events. Climate change impacts, combined with land use changes that alter hydrology patterns, may increase the vulnerability of road drainage structures to damage. Failing culverts can affect the condition and function of roads, increase repair and maintenance costs, and add to water quality problems in adjacent waterways.

Newer designs and materials for culverts can improve their capacity and functional lifespan. For example, in some places galvanized steel pipe culverts were placed in locations where water is increasingly brackish as a result of sea level rise or exposure to storm surge. Replacement of older materials with high-density polyethylene pipes can reduce deterioration and maintenance needs. Replacing culverts with increased size and flow capacity can improve performance in extreme rain events and add long-term capacity for a changing climate.

as evacuations in response to flooding or coastal storms. Similarly, people who depend on public transit – those who are without cars or unable to drive – are often more vulnerable under conditions when transportation systems are disrupted. Low-income residents are also affected greatly by impacts to transportation and energy systems. Lack of access to work can have disproportionate impacts on low-wage workers. Low-income neighborhoods are also more likely to suffer from additional stressors, such as poor condition of aging infrastructure. In addition, communities with a high proportion of manufactured homes can be vulnerable to greater impacts from wind damage in severe storms.

9.4.3. Structural and Operational Impacts – Extreme Weather Events Impacts to Human-Built Infrastructure

Climate change impacts to the structural and operational use of infrastructure are particularly vulnerable to increasing frequency and/or intensity of extreme weather events. Back-to-back storms or cascading events can lead to the shutdown of public transit and power outages, dramatically increasing the vulnerability of residents and businesses dependent on infrastructure services. Although infrastructure managers typically have continuity plans[c] and emergency management procedures, these response strategies may need to be expanded or enhanced to prepare for greater variability in extreme weather events.

Climate impacts may be direct, such as physical damage to structures as a result of extreme weather events or sea level rise. Climate impacts may also have significant effects on the operability of infrastructure; for example, increasing salinity as a result of sea level rise may affect water use in power generation or industrial systems. Direct impacts can have significant costs for repair or replacement, or may require changes in technical design or materials. Impacts to operations that result in disruption of services can have wide-ranging and long-term impacts on economic productivity. In addition, both short-term and long-term impacts can affect public safety and economic productivity. Planning and operational decision making are essential to managing repair, recovery, and restoration of infrastructure services.

When infrastructure is damaged or impaired by weather-related impacts, the immediate focus is on the need to restore services with repairs to make the infrastructure operable. Taking a long-term approach to damage recovery can improve the resilience of infrastructure to future impacts.

[c] Continuity plans are a planning tool to ensure the continued performance of essential functions under a broad range of circumstances. These are used both by government agencies and businesses, and may be developed as part of disaster recovery plans.

For example, improving resilience could include reinforcement or replacement of structures, changes to the system location or design, or additional construction to add redundancy to the system. However, upgrading and improving culverts to meet higher capacity demands can be complicated by regulatory constraints. For example, federal emergency funds for road repairs in response to washouts may be limited to in-kind replacement. These restrictions may be changing as the Federal Highway Administration, Federal Emergency Management Agency, and others are adopting practices to plan for potential climate change impacts.[58]

Delaware often receives wintry-mix storm precipitation. Winter rain falling on snow can result in heavy, slushy snowpack, which sticks to roads and refreezes at night. These conditions can cause ice dams to plug drainage systems, leading to roadway flooding and overtopping of bridges and culverts. In addition, this heavy snow mix can be difficult to remove from roads with conventional snow plows, resulting in icy, bumpy, and dangerous roadways.[59]

Impacts to Natural Infrastructure

Natural environments that provide valuable ecosystem services are also vulnerable to impacts from extreme weather events and increasing erosion, which may be exacerbated by sea level rise. Tidal wetlands in all coastal regions of Delaware are already declining where shoreline erosion rates exceed sediment accretion rates. Studies have indicated that Delaware's coastal wetlands have, historically, moved inland as sea level rises.[60] However, with rising sea levels and potentially greater intensity of coastal storms, further losses of wetland habitat may impair their ability to buffer inland areas, store floodwater, and act as a sink for nutrients and pollutants.

Beaches and dunes are also exposed to sea level rise and the associated impacts of coastal erosion and flooding. Barrier beaches in Sussex County are particularly vulnerable to loss of beach habitat, as coastal development blocks the landward migration of the beach and dune system. As a result, beaches and dunes decrease in width and height, thus reducing their function in providing a physical buffer that protects buildings and infrastructure on the shoreline and inland bay side of barrier beaches.

Maintaining Coastal Buffers – Beach Nourishment

Adding sand to an eroding beach is a costly but effective method to maintain a safeguard between the ocean waves and shoreline structures, reducing storm damage and enhancing recreation opportunities. Increasing the beach width acts as a buffer to absorb wave energy from storms.

In Delaware, beach nourishment has been used as a management strategy for maintaining public beaches along the Atlantic coast, including in Rehoboth, Dewey, Bethany, South Bethany, and Fenwick Island since 1961. Beach nourishment projects typically involve pumping sand onto a beach directly by dredge pump from an offshore sand source (borrow site). Beach fill projects, where sand is hauled in by truck, have also been used in Delaware Bay beach communities, including Bowers Beach, South Bowers Beach, and Kitts Hummock.

Although there is increasing demand for beach nourishment projects to maintain public beaches and support the coastal tourism industry, there are also residential communities that look for beach replenishment strategies to protect homes from storm and flooding damage. Delaware's state policy is to consider economic costs and benefits in determining where, or whether, to pursue beach nourishment projects. A recent economic study focused on seven Delaware Bay beach communities evaluated the estimated costs and benefits of beach nourishment against "no action" and "retreat" alternatives. These beaches are vulnerable to impacts from increasing frequency and intensity of coastal storms as well as current erosion and flooding problems. Incorporating projected sea level rise will add a new dimension to short-term and long-term planning.

9.4.4. Roads and Dams – Increased Precipitation and Flooding

Because of Delaware's low-lying topography and location within three major watersheds, flooding is a frequent occurrence in many parts of the state. Changes in precipitation patterns may lead to a greater extent and/or frequency of inland

Critical Transportation Infrastructure – Delaware's Early Warning System for Road Conditions

The Delaware Department of Transportation (DelDOT) manages a wide range of technologies for monitoring traffic flow, road and bridge conditions, and potential hazards that may require rapid response to keep transportation moving safely and efficiently. Transportation networks are one of the "critical infrastructure" systems that are in continuous operation, and damage or disruption to critical infrastructure can have significant impacts to public safety and economic activity.

Improving data collection and analysis can advance Delaware's ability to prepare for and respond to changing climate and weather extremes. Currently, DelDOT operates a system of 17 weather monitoring stations using sensors embedded in pavement or on towers or poles to monitor road surface and weather conditions along critical sections of the state's transportation system. The system collects real-time weather data, including air temperature, humidity, precipitation, wind, and visibility (both current conditions and 24-hour averages), and also records road surface conditions and temperatures.

Delaware transportation managers are evaluating ways to expand the existing monitoring system by adding data sensors that measure water levels and flows. By improving the data collection and analysis of both surface and hydrologic conditions, planners will be able to make better predictions of flooding hazards, provide early warning information to local emergency managers, and prepare for adjustments to traffic flows, such as detours and evacuation routes.

The combined data collection, analysis, and modeling are tools for a "decision support system" that can evaluate conditions, forecast impacts, and communicate risks to community leaders and emergency managers. In addition to contributing to emergency preparedness, this kind of decision-making process can help planners evaluate options for recovery and repair of damaged infrastructure after a severe weather event.

flooding and increase the potential vulnerability of infrastructure in flood-prone areas. With potential increases in precipitation falling in more intense storm events, the higher volume and velocity of surface runoff and streamflow can result in rapid erosion and scouring. This can erode roadway banks and pavements, undermine structural supports, and result in weakened or washed-out roads, rail, bridges, and culverts and other drainage structures.

Of the 48 regulated dams in Delaware, 42 are owned by the State of Delaware and managed by the state's Department of Transportation or the Department of Natural Resources and Environmental Control. Many of these dams are located adjacent to or integrated into state-managed roads and bridges. In extreme rain events, dams may be vulnerable to damage or failure. Thus, roads or bridges located on top, next to, or downstream from these structures are at risk of flooding or washout.

A potential shift toward more winter precipitation falling as rain instead of snow may alter the amount of snowpack in upstream portions of the Piedmont Basin. This may result in changes in the timing of spring thaw and shifts in seasonal flows and water levels that could increase flooding, particularly in urban areas of northern Delaware, where a high percentage of impervious surfaces already contributes to severe stormwater runoff problems.

Delaware already faces challenges from flooding and drainage problems, both in coastal areas and inland floodplains. Climate change impacts associated with sea level rise and extreme rain events are likely to result in more frequent and extensive flood problems that compound or magnify other stressors. Heavy precipitation events and resulting peak streamflows can exacerbate existing flooding problems. Delaware is already experiencing changes in streamflows. For example, floods that exceed the 10-year recurrence interval have become more frequent along the Brandywine Creek since the 1970s.[61] Flooding impacts to roads and rail lines also affect energy production, particularly for coal-fired power generation that relies on coal transport by rail. Transmission structures such as power lines and electrical substations are often built to withstand minor flooding; however, extreme weather events with high winds can cause significant damage and disruption to service.

Increased precipitation and associated flooding may increase the vulnerability of remediation sites and landfills associated with industrial facilities. Inundation from flooding may trigger the movement of hazardous chemicals or pollutants into groundwater or surface water, potentially affecting industrial operations. Increasing storm intensity may also increase the height of storm surge, causing greater extent of flooding than previously experienced.

9.4.5. Energy Production and Structural Safety – Increasing Temperatures

Rising summer temperatures and extended heat waves have been experienced in many parts of the United States in recent years. The summer of 2012 was the hottest summer on record, and also one of the driest. By late September 2012, more than 60 percent of the contiguous United States, including Delaware, was experiencing moderate to exceptional drought.[62] Increased variability of extreme temperatures is likely to have significant impacts on both natural and human-built infrastructure.

Under heat wave conditions, peak demands for electricity in summer months increase dramatically and vulnerability to power outages can affect wide regions. For example, in July 2012, a power outage during a record heat wave resulted in 1.7 million people across 10 states being without electricity for 2 days or more. Power outages may be triggered directly or indirectly by high heat events. Thermal stress or damage to energy infrastructure from heat-driven storms can impair electricity transmission. Higher air and water temperatures, or lack of available water for cooling, can affect operations and reduce electricity output. Power generators in Delaware and neighboring states (which provide electricity to meet in-state demand) are likely to experience local and regional shortages during extreme peak demand. Summer droughts also increase demand for irrigation, which in turn drives energy demands for pumping groundwater.

Power generation facilities can be affected by changes in water salinity and temperature. Drought conditions tend to push the salt line up the Delaware River; this increased salinity can affect the availability and function of cooling water needed for power generation and other industrial uses. Increased water temperatures during extended heat waves can trigger shutdown of power plants. For example, in August 2012 the Millstone Nuclear Power Station in Waterford, Connecticut, was forced to shut down for 12 days when Long Island Sound water temperatures exceeded the limit of 75˚F.

Increased heat can accelerate deterioration of infrastructure, such as heat stress in structural supports and exposure of pavement to high heat. Buckling or rutting of asphalt may occur on roads or runways. These impacts may require increased maintenance and more frequent monitoring to prevent damage and ensure public safety. However, high heat conditions can complicate road maintenance and repair operations; health restrictions for outdoor workers may limit road work to nighttime hours to avoid high heat and ozone risks.

9.4.6. Transportation and Energy Facilities – Sea Level Rise

The potential effects of sea level rise from climate change have been extensively studied, particularly in the Mid-Atlantic coast region where rates of sea level rise are higher than the global average.[d] In Delaware, a vulnerability assessment conducted by Delaware Coastal Programs presented three scenarios for sea level rise by 2100 that are based on low, moderate, and high levels of future global warming.[e] The Low scenario is 1.6 feet (0.5 meter),

d The Mid-Atlantic region is described by Titus (2009) as the eastern U.S. coast from New York to North Carolina. Tide gauge observations over the 20th century indicate that relative sea level rise (the combination of global sea level rise and land subsidence) rates were higher than the global mean and generally ranged from 2.4 to 4.4 millimeters per year, or about 0.3 meters (1 foot). Over the same period, global average sea level rose approximately 1.7 millimeters per year. Source: Titus, J.G. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.1., p. 2.

e Further discussion of sea level rise is found in the methodology section of Chapter 1, Introduction and Methodology.

Table 9.4. Potential impacts of sea level rise to human-built infrastructure in Delaware

Infrastructure Affected	*Area in Delaware Affected*	*Potential Impacts Under Sea Level Rise Scenarios*
Roads and bridges; evacuation routes	Roads and bridges throughout the state, particularly in the Inland Bays area and around Lewes. Many Delaware Bay beach communities may be affected by sea level rise cutting off their primary access roads and evacuation routes. In New Castle County, portions of State Route 9 are also vulnerable to severe flooding from sea level rise.	Statewide, an estimated 12.6 miles of designated evacuation routes could be inundated under the Low scenario of one-half meter of sea level rise.[64]
Public bus transit	Primarily New Castle County, which has the largest concentration of DART bus service routes. Urban passengers and particularly transit-dependent residents are likely to be affected.	An estimated 36 to 94 miles of bus routes and 14 to 58 bus stops could be subject to inundation in New Castle County. (The range reflects the Low-to-High sea level scenarios of 1.6 to 4.9 feet, or 0.5 to 1.5 meters.)[65]
Passenger and freight rail lines	Passenger rail in northern New Castle County, especially Wilmington. Rail interchanges to central and southern Delaware; for example, the movement of coal to the Indian River Generating Station and grain to poultry growers in southern Delaware relies on freight rail connections north of the C & D Canal.	An estimated 8 to 21 miles of rail line in the Wilmington area (under the 1.6 to 4.9 feet sea level rise scenarios).[66]
Marine transport facilities	The Port of Wilmington is a major facility that could be significantly affected. Public boat ramps and piers throughout coastal Delaware are also at risk for intermittent or chronic flooding as a result of sea level rise.	An estimated 78 acres – approximately 36 percent – of the port's main facilities could be inundated under the Low scenario of 1.6 feet of sea level rise.[67] 60 percent of boating facilities statewide could be affected under the Low scenario.[68]
Energy and industrial facilities	Facilities located along the Delaware River and in the Inland Bays are vulnerable to inundation from sea level rise, and potential changes in salinity may affect industrial operations.	Between 16 and 25 percent of the acreage of heavy industrial lands in the coastal areas could potentially be affected under the three sea level rise scenarios.[69]

Intermediate scenario is 3.3 feet (1 meter), and High scenario is 4.9 feet (1.5 meters).[63] Based on a spatial analysis of the three scenarios using a "bathtub model,"[f] the Delaware Sea Level Rise Vulnerability Assessment identified infrastructure resources that could be vulnerable to sea level rise over the next century. **Table 9.4** summarizes the potential impacts to human-built infrastructure, based on this assessment.

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