IEc

An Economic Analysis of the Impacts of Climate Change in the State of Delaware

Final Report | Released July 2022

prepared for:
DNREC

prepared by:
Industrial Economics, Incorporated
2067 Massachusetts Avenue
Cambridge, MA 02140

TABLE OF CONTENTS

This project was partially funded using federal funds under award NA18NOS4190144 from the Delaware Coastal Programs and the Office for Coastal Management, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The statements, findings, conclusions and recommendations in this report are those of the author(s) and do not necessarily reflect the views of the Office for Coastal Management, National Oceanic and Atmospheric Administration or the U.S. Department of Commerce.

Suggested citation

Industrial Economics, Incorporated. 2021. An Economic Analysis of the Impacts of Climate Change in the State of Delaware. Prepared for the Delaware Department of Natural Resources and Environmental Control.

ACRONYMS

CIRA	Climate Change Impacts and Risk Analysis
CMIP5	Coupled Model Intercomparison Project (Phase 5)
DDA	Delaware Department of Agriculture
DelDOT	Delaware Department of Transportation
DHSS	Delaware Department of Health and Social Services
DNREC	Delaware Department of Natural Resources and Environmental Control
DSHS	Delaware Department of Safety and Homeland Security
EMS	Emergency medical services
EPA	U.S. Environmental Protection Agency
EPIC	Erosion Productivity Impact Calculator
FEMA	Federal Emergency Management Agency
GCM	General circulation model
GDP	Gross domestic product
HUC	Hydrologic unit code
LOCA	Localized Constructed Analogs
NASS	National Agricultural Statistics Service
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathway
SLR	Sea level rise
VSL	Value of statistical life

CHAPTER 1 | INTRODUCTION

This report, *An Economic Analysis of the Impacts of Climate Change in the State of Delaware,* explores the multi-sectoral economic impacts of climate change that Delaware may face over the coming decades. It builds on the 2014 Delaware Climate Change Impact Assessment, completed by the Delaware Department of Natural Resources and Environmental Control (DNREC).[1] This report aims to support state agency decision-making on climate change, particularly in relation to strategies outlined in Delaware's Climate Action Plan. Specifically, this report provides Delaware's state agencies, including the DNREC, Department of Health and Social Services (DHSS), Department of Transportation (DelDOT), Department of Agriculture (DDA), and Department of Safety and Homeland Security (DSHS), with an estimate of the economic impacts of climate change for a "status quo" future, as compared to a "no climate change" baseline. A "status quo" future assumes that no additional climate adaptation will be undertaken, beyond efforts already funded or likely to occur within existing budgets and public responsibilities in response to climate change. The results of this report are intended for use as an economic baseline from which the benefits and costs of potential adaptation actions can be measured.

In Chapter 1, we provide an overview of the methods, results, and limitations of this analysis. Chapter 2 provides more information on the analysis framework and climate projections used to estimate economic impacts. Chapters 3 through 7 present climate change impacts for five sectors, organized by the state agencies listed above. Appendix A presents a glossary of technical terms used throughout this report, and Appendix B provides more details on the climate data used in the analysis.

1.1 OVERVIEW OF METHODS

This analysis models the economic impacts of climate change across five sectors: natural resources, health, transportation, agriculture, and public safety. The estimates in this analysis cover 26 impact categories but do not represent the full universe of economic impacts of climate change in Delaware. To model future climate change for the state of Delaware, we use two climate forecasts and one sea level rise (SLR) projection. The two climate forecasts are defined by RCPs, or representative concentration pathways, which are scenarios that make certain assumptions about future carbon dioxide (CO_2) and other greenhouse gas emissions. RCP4.5 and RCP8.5 represent a lower and a higher emissions pathway respectively.[2] The SLR projection estimates that statewide SLR will reach 0.75 ft by near century (2020-2039), 1.5 ft at mid-century (2040-2059), and 3.0 ft by late century (2080-2099), relative to sea level in the year 2000. Future storm surge impacts are evaluated for the 1-percent and 10-percent storm events, as defined by current storm frequency and intensity.

The economic impacts of these changes are evaluated across a total of 26 impact categories,[3] presented in **Table 1-1**. These categories are organized into the same five sectors, corresponding

---

[1] Delaware Department of Natural Resources. 2014. Delaware Climate Change Impact Assessment. Division of Energy and Climate. Available at http://www.dnrec.delaware.gov/energy/Documents/Climate%20Change%202013-2014/DCCIA%20interior_full_dated.pdf

[2] RCPs are defined in work by the Intergovernmental Panel on Climate Change (IPCC).

[3] All impact estimates presented in the report incorporate future population and GDP growth using consistent assumptions across models.

to the state agencies that manage them. Each state agency shown in the table assisted in defining these categories and providing data; additionally, each of these agencies were consulted for feedback throughout the analysis.

The economic impact models used in this report draw on existing climate impact literature and previous assessment reports, including the U.S. Environmental Protection Agency's (EPA's) 2017 Multi-model Framework for Quantitative Sectoral Impacts Analysis report.[4] Economic impact measures vary by sector but can generally be categorized in five groups: lost revenues (e.g., crop production losses and lost wages); direct expenses (e.g., infrastructure repair costs, direct costs of hospitalization); fatal risk (e.g., willingness-to-pay to avoid fatal human health risk); delay costs (i.e., the lost perceived value to society associated with transportation delays); and other economic welfare (e.g., willingness-to-pay for improved water quality).[5] Chapter 2 of this report provides more detail on the elements of the analysis framework.

TABLE 1-1. CATEGORIES OF ECONOMIC IMPACT

Natural Resources (DNREC)	Health (DHSS)	Transportation (DelDOT)	Agriculture (DDA)	Public Safety (DSHS)
• Municipal & Industrial/ Irrigation Water Supplies • Water Quality • Invasive Species • Native Species • Ecosystem Services • Water Quality, Waste Treatment • Contaminated Soil Flooding	• Heat Related Mortality and Morbidity • Lung and Respiratory Disease • Allergens and Mold • Vector-Borne Disease	• High and Significant Hazard Dams • Roads, Rail, and Bridges structures • Culverts and Road Closures • High Tide Flooding	• Saltwater Intrusion and Inundation • Crop Growth • Irrigation Water • Agricultural Wages • Invasive Species on Cropland • Milk Production • Poultry Heating and Cooling	• Emergency Services Response Time • Access and Upkeep of Evacuation Routes • Frequency of Emergency Responses • Limited Access to Cooling Centers

The results of each impact category analysis is presented at the county level for three eras: near century (2020-2039), mid-century (2040-2059), and late century (2080-2099), as compared to a "no climate change" baseline era. In this way, the economic impacts estimated are directly attributable to projected changes in climate.

---

[4] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001. Note also that the term "economic impacts" have different meanings in different contexts. We use the term as it is most often applied in the climate change literature, as a broad, generic definition of the effects of climate change, denominated in monetary terms. In that context, economic impacts can include changes in economic welfare, revenue losses, costs to repair damage, or a range of other effects. In other contexts, economic impacts are defined as economy-wide effects on a national and regional scale, including changes to employment, GDP, or value-added — a definition that often specifically excludes most of all economic welfare effects.

[5] Note that fatal risk and delay costs were also considered welfare measures, but we present them separately due to their magnitudes. A strict economic welfare theoretic approach would replace revenue effects with profits, or wages with net lost income, because firms or individuals that experience revenue or wage loss could theoretically change business or employment. Our estimates of lost revenue are relatively small, so we do not focus on this distinction.

1.2 ECONOMIC IMPACTS SUMMARY

This section summarizes the projected multi-sectoral impacts of climate change in Delaware, estimated using the methods described in Chapter 1.1 above.

Figure 1-1 presents the total annual projected economic impacts for each of the five sectors across the three future eras. Sectors vulnerable to temperature and precipitation changes have two estimates per era (one for each GHG emission scenario, or RCP) which are presented separately in the summary graphics in this chapter. Sectors vulnerable to SLR have a single impact estimate per era, which is added to each of the RCP results for the purposes of summarizing the total magnitude of expected impacts by era.[6] Storm surge impacts are presented separately, for reasons explained more fully below and in Chapter 2.2. The total economic impact by late century for all five sectors is well over $1 billion annually (2019$). All sectors are expected to experience a noticeable increase in impacts by late century as compared to the earlier portion of the century. This increase is particularly prominent in the transportation sector, which sees a 12-fold increase under both the high and low emission scenarios, primarily driven by temperature, precipitation, and high tide flooding delays on roads. In contrast, natural resource damages, driven by water quality and ecosystem services losses, result in high levels of economic impact early in the century, which continue to grow through late century.

FIGURE 1-1. ANNUAL ECONOMIC IMPACTS OF CLIMATE CHANGE BY SECTOR

Statewide economic impacts of climate change, including the effects of projected SLR, across the five sectors, for RCP4.5 and RCP8.5. SLR impacts are era-specific and are assumed constant across RCPs. Totals do not include the impacts of storm surge. Values are reported in 2019 dollars.

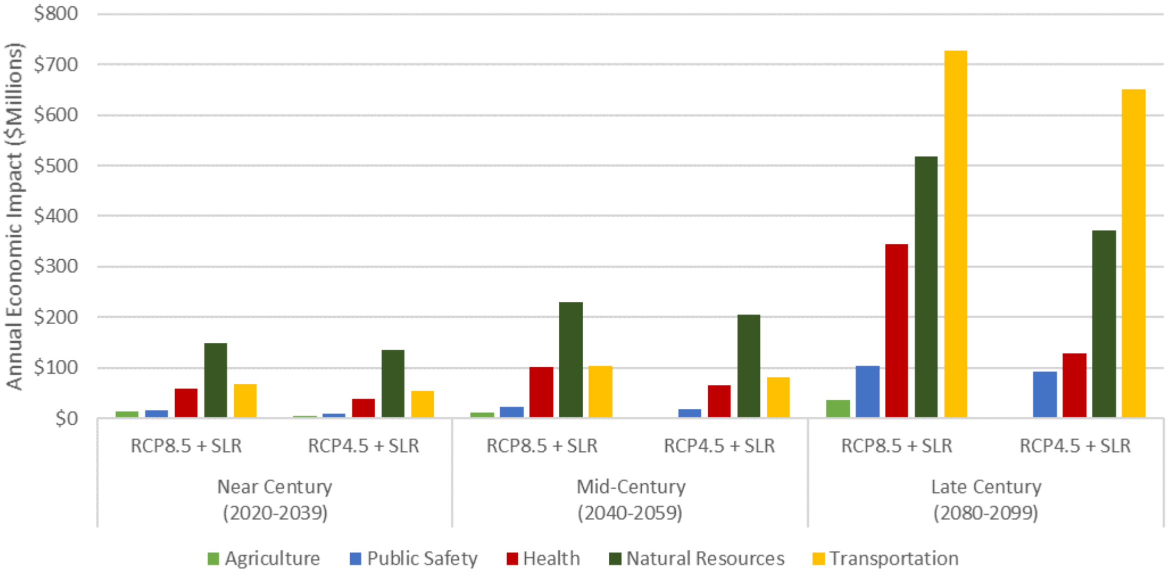


Figure 1-2 presents the results over the same time period but broken down by economic impact measure rather than by sector. Delay costs are the highest impact measure by the end of century.

---

[6] Due to interactions between emissions, warming, and SLR, expected sea level under the RCP4.5 greenhouse gas emissions scenario is likely to be lower than sea level under RCP8.5, particularly in the late century. SLR is, however, not only a function of warming but also a number of non-RCP defined factors such as land subsidence and ice sheet melting. The single SLR pathway analyzed in this report is likely to fall somewhere between the likely pathways associated with the two RCPs analyzed. See Chapter 2.2 for further discussion.

Fatal risk and economic welfare measures show similarly high damages, particularly by the end of the century. Lost revenues, the impact category with the smallest value, still reach nearly $31 million per year under RCP8.5 by the end of the century.

FIGURE 1-2. ANNUAL ECONOMIC IMPACTS BY IMPACT MEASURE

Statewide economic impacts of climate change, including the effects of projected SLR, across the four impact measures, for RCP4.5 and RCP8.5. SLR impacts are era-specific and are assumed constant across RCPs. Economic impacts are measured using several valuation techniques in this analysis. Lost revenues include crop production, dairy production, and agricultural wages. Direct expenses include a variety of repair, replacement, and other out of pocket expenses. Fatal risk is used for health outcomes and represents willingness to pay to avoid increased mortality risk. Welfare impacts include ecosystem service losses and willingness-to-pay for improved water quality. Delay costs represent the value of lost time due to transportation delays. Totals do not include the impacts of storm surge. Values are reported in 2019 dollars.

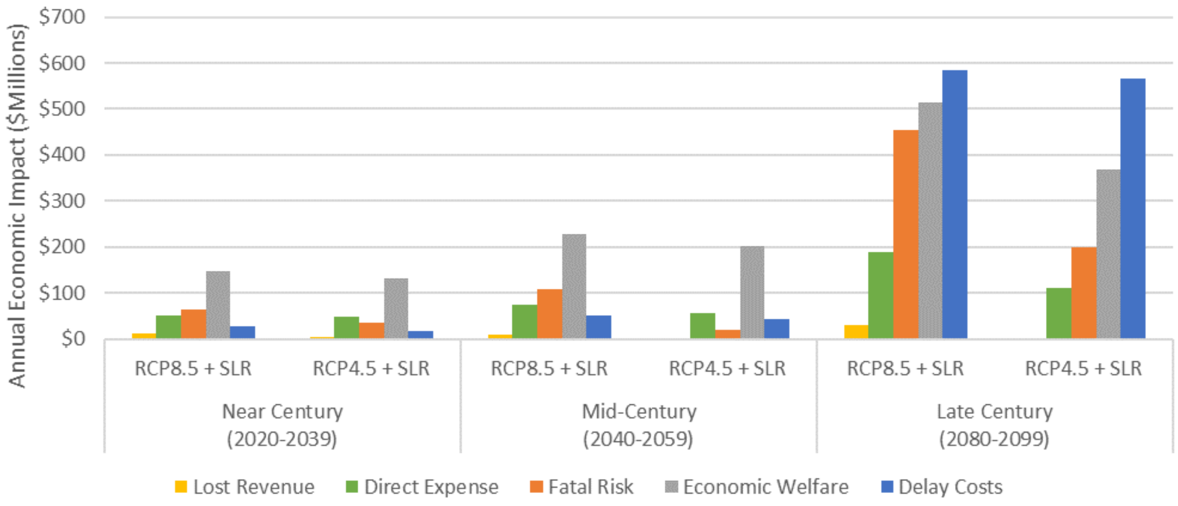


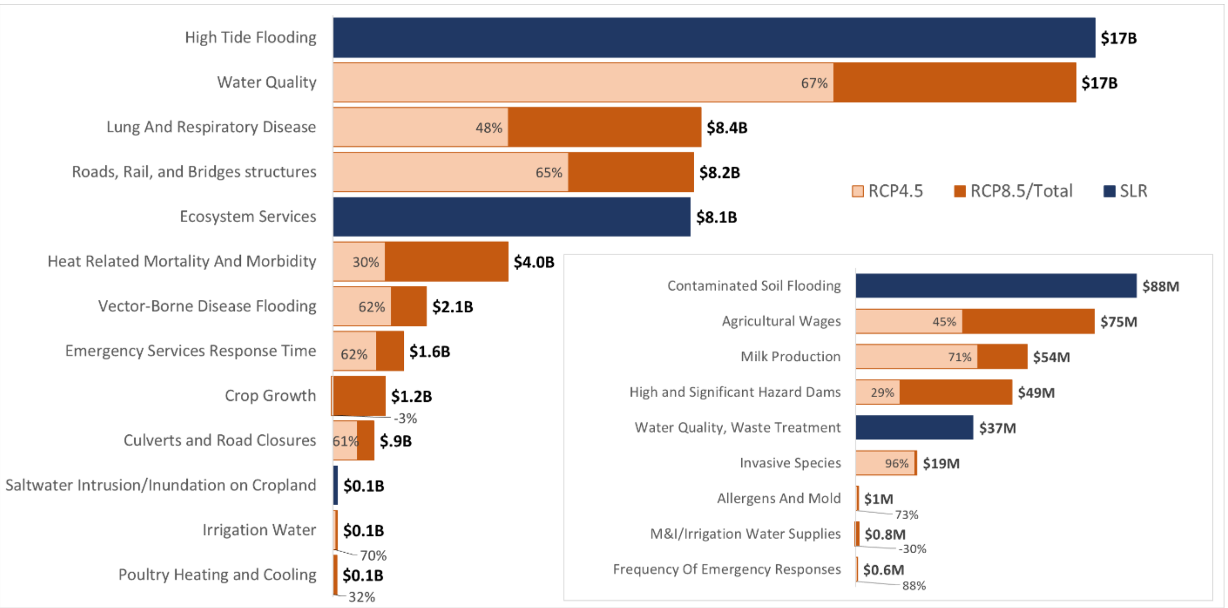
Figure 1-3 shows cumulative impacts by category, from 2020 to 2099 (excluding storm surge impacts). When summed across the century, and across all impact measures, cumulative potential economic impacts of climate change total over $69 billion for the state.[7] High tide flooding (an impact category driven by SLR) and water quality (a category impacted by temperature and precipitation changes), have the highest cumulative impacts at $17 billion each under RCP8.5. On average, across all non-SLR categories, RCP4.5 impacts are 57 percent of those under RCP8.5 for the century. In other words, a change in greenhouse gas emissions trajectory from RCP8.5 to the lower emission RCP4.5 reduces economic impacts by 43 percent.

---

[7] $74 billion represents the non-discounted total economic impacts; the same series of impacts discounted at 3 percent is $18 billion.

FIGURE 1-3. CUMULATIVE ECONOMIC IMPACTS OF CLIMATE CHANGE BY CATEGORY (2020-2099)

The blue bars represent impact categories affected by SLR, while the orange bars represent categories affected by temperature and precipitation changes, as quantified by the RCP scenarios. For the orange bars, the light orange portion represents impacts under RCP4.5, while the full bar represents damages under RCP8.5. Also, for the orange bars, the percentages shown in the middle of the bar represent RCP4.5 impacts as a percentage of total impacts under RCP8.5 (the bolded values at the end of the bar). The inset shows all categories with cumulative damages less than $0.5 billion. Totals do not include the impacts of storm surge. The figure does not include the following impact categories: native plant species and nuisance species in agriculture (no quantitative impacts estimated); access and upkeep of evacuation routes (storm surge impacts only); and limited access to heating and cooling (a subset of heat related mortality and morbidity). Values are reported in 2019 dollars.

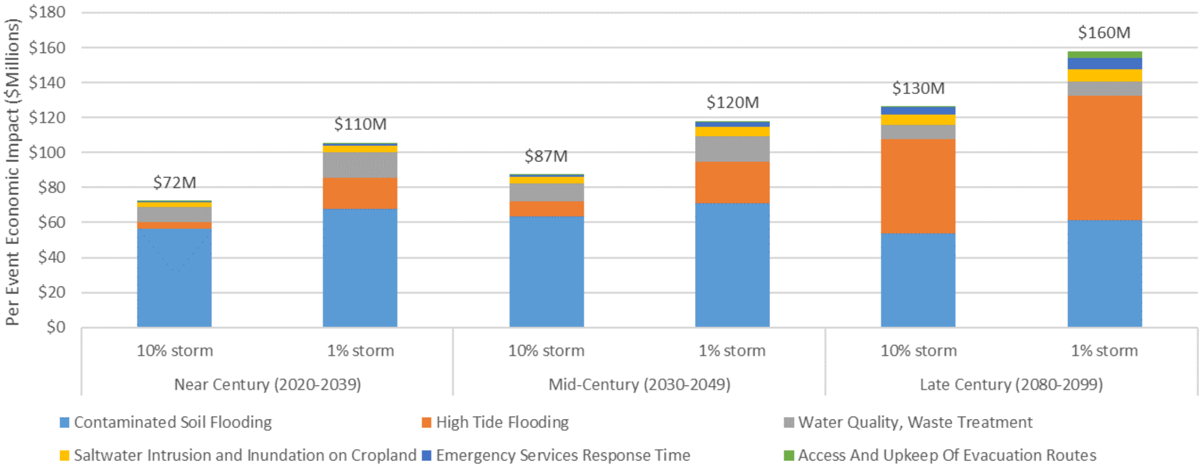


Notice that the results shown on **Figures 1-1** through **1-3** include impacts from temperature and precipitation changes (i.e., from the two RCP scenarios) as well as from SLR (i.e., from one SLR projection) but do not include storm surge impacts (computed for the 1-percent and 10-percent storm events, as defined by current storm frequency and intensity). This is because the impacts shown above were estimated on an annual basis, whereas storm surge impacts were estimated on a per-event basis. The 1-percent storm has a 1 percent likelihood of occurring in any given year (based on current tide gauge records) which means that there will be many individual years in which no storm surge impacts occur, with all the impacts then concentrated in the single year in which that storm actually takes place. The same is true for the 10-percent storm. One possible approach to calculating annual costs associated with these individual storm surge events would be to multiply the total damages by the likelihood of occurrence. For example, if the 1-percent storm is projected to cause $100 million in impacts, we could assume that storm has an annualized impact of $1 million per year. This approach, however, is incomplete in its estimation of impacts if we only consider the 1-percent and 10-percent events (as we do in this report). This approach neither accounts for the damages caused by more frequent but lower-impact storms (e.g., a 20-percent storm, a 50-percent storm) nor less frequent but higher-impact storms (e.g., a 0.1-percent storm, a 0.01-percent storm). For this approach to adequately estimate storm surge impacts per year, it requires the full range of storm surge events to be considered, from frequent, small storms to very infrequent, large storms. For this reason, this report presents storm surge impacts on an event basis, with Chapter 2.2 discussing this further.

Thus, separate from the results presented above, **Figure 1-4** presents the economic impacts of storm surge for the 1- and 10-percent events in each era. The size of these 1-percent and 10-percent events were estimated based on current conditions, and given the significant uncertainty around how these storm surge events will change in the future, we do not account for changes in the magnitude of the 1-percent and 10-percent events over the course of the century. However, even if the magnitude of these two storm surge events are treated as unchanging over the three eras, the impacts of the surge events change over time due to SLR (i.e., the inundation zone from storm surge is pushed inland as sea levels rise). For most of the relevant impact categories, this results in a reduction in storm surge impacts over the century, as more of the vulnerable assets concentrated along the coast fall within the SLR inundation zone, while the storm surge inundation zone moves beyond the area of concentrated infrastructure. High tide flooding is the one exception, where storm surge impacts include episodic flooding within the SLR inundation zone.

FIGURE 1-4. ECONOMIC IMPACTS FROM STORM SURGE EVENTS

Results shown below are the estimated impacts associated with two storm surge events: a 1-percent and 10-percent event, with results separated by impact category. The two storm events are defined by their likelihood of occurring under current climate conditions. Values are reported in 2019 dollars.



1.3 KEY LIMITATIONS FOR THE INTERPRETATION AND USE OF THESE ESTIMATES

There are several limitations that should be acknowledged when interpreting and using the findings in this report:

- This analysis defines a baseline against which the benefits and costs of new climate change adaptation actions can be evaluated. Therefore, the scenarios we present assume a “status quo” with respect to adaptation measures currently being used by state agencies and fixed implementation of potentially relevant state and Federal policies, such as water quality regulations that might prompt action to remediate pollution events. In constructing a “status quo” situation, we have attempted to capture the climate resilience actions and investments already made in Delaware; however, in many sectors, information on the extent of those existing actions and investments is limited. Consequently, future impacts may be lower if additional adaptation measures of which we are unaware are already being taken in the private or public sector.

- The 26 impact categories do not represent the full universe of economic impacts of climate change in Delaware. Additional impacts not covered by this report, but which have been analyzed and quantified in recent economic impact literature, include impacts to privately owned coastal property; effects of temperature and extreme events on the supply of, demand for, and transmission and distribution of electric energy (as well as other means of indoor heating and cooling); effects of inland and urban flooding; impacts of extreme heat on workplace productivity, health, and mortality; impacts of temperature on the rate of violent and property crime; impacts of temperature and precipitation changes on outdoor recreation patterns; and impacts on beach replenishment costs. In addition, other categories of impacts, such as the structure and function of ecosystems, and cascading or cross-sectoral impacts, particularly in the infrastructure sector, have been incompletely quantified in the literature. As such, these impacts are not reflected in this report but should be acknowledged as components of the overall economic impact of climate change on Delaware.
- Many of the impact category analyses make simplifying assumptions and/or rely on national data in place of locally available figures, due to data availability issues. These instances are noted in the "Limitations" section of each chapter, with a note about the possible implications of each data limitation (where known).
- Despite the above limitations, the estimates presented in this report represent the likely magnitude and direction of expected impacts. The estimates are well supported by a wide range of peer-reviewed research and analysis conducted over the past decade. Therefore, this analysis provides a useful and extensively supported set of estimates for policymakers. Such estimates are particularly well-suited to inform future decision-making on the benefits and costs of climate change adaptation measures designed to limit Delaware's exposure to economic climate change risks.

CHAPTER 2 | ANALYSIS OVERVIEW

IEc worked closely with DNREC to both define consistent parameters for this study and gather the necessary data for the analysis of each impact category. A core goal of each analysis was to provide estimates that would be immediately useful to various state agencies in their climate action planning processes. Therefore, we aimed to use data sources consistent with those currently in use; analyze climate scenarios and impact categories that were of interest to Delaware's state agencies; and produce results that are meaningful and useful to plan for climatic stressors that affect Delaware and its residents. Where we use outside data or differ from previous analyses, we provide an explanation of why that choice was made and how it might affect the interpretation of results.

2.1 ANALYSIS SCENARIOS AND ASSUMPTIONS

This analysis covers three future time periods, or eras, which are compared to a "no climate change" baseline era. The future eras are defined as follows:

- Near Century (2020-2039)
- Mid-Century (2040-2059)
- Late Century (2080-2099)

These periods are chosen to be consistent with climate and impact projections made in the 2014 Delaware Climate Change Impact Assessment. In addition, we calculate cumulative impact estimates by linearly interpolating annual impacts between eras and summing, beginning in 2020.[8]

The overall goal of our analyses was to identify economic impacts that can be directly attributed to projected changes in climate — or in other words, the incremental impact of climate above a "no climate change" baseline. In some cases, the incremental effect is calculated by subtracting a baseline, "no climate change" economic impact estimate from the comparable economic impact estimate for the 20-year future era. In other cases, the incremental impact of changing climate is inherent in the method applied. For example, some methods provide an estimate of economic or physical impact for any incremental temperature change, so the difference in temperatures between the baseline and future periods is used as an input in the method. Details are provided in the relevant sections for each impact category.

The target common spatial scale of the reported results is the county level. Where data are spatially available at a finer scale (e.g., contaminated soils, ecosystem services, wastewater systems), results may be presented in maps and figures. County-scale future population projections are obtained from the EPA's Integrated Climate and Land Use Scenarios version 2,

---

[8] This process introduces the simplifying assumption that impacts increase linearly between eras. A more precise estimate would rely on annual impact estimates from all impact categories; however, annual results were not available for all categories.

consistent with those used in the U.S. EPA's Climate Change Impacts and Risk Analysis (CIRA) study, which itself forms the basis for many of the analyses described in this report.[9]

Economic impacts are reported as adverse impacts, meaning *positive* reported values of economic impacts in the summary tables represent adverse effects due to climate change while *negative* values represent *benefits*, relative to the baseline. We use "economic impacts" as a general term but provide further detail about how impacts are defined in each section. Unless otherwise indicated, economic impacts are presented in undiscounted 2019 U.S. dollars. Where necessary, values have been adjusted for inflation using the Bureau of Labor Statistics Consumer Price Index.[10] Results are presented to two significant digits except for impacts less than $1,000, which are indicated as "<$1,000".

Table 2-1 presents the 26 impact categories analyzed (by sector), the measure of economic impact estimated, and the climate stressors considered in each analysis. The methods applied to estimate economic impact often provide results in terms of market impacts — such as the crop revenue lost when there is insufficient irrigation water, the medical cost to treat an illness, or the expense to repair a road or bridge damaged by a climatic hazard. In other cases, we apply well-established methods to estimate economic impact where no market transaction takes place, such as when an individual dies prematurely from a climatic hazard or when water quality is impaired. In cases where no market price is available to provide a valuation estimate, the method to estimate economic impact involves the use of welfare economic techniques, which are often used to estimate what individuals would be willing to pay to avoid the risk of an undesirable outcome. The welfare economic methods applied in this report are well-established in the economics profession and are supported by a wide range of peer-reviewed literature — their application represents standard practice for valuation of the avoidance of environmental and health risks where no market price is available. More details on the definitions of each category, as well as the results of each analysis, can be found in Chapter 3 through Chapter 7.

---

[9] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.

[10] Bureau of Labor Statistics (BLS). (2020). All Urban Consumers (Current Series) Consumer Price Index-CPI. Accessed on 17 Sep 2020. Available at https://www.bls.gov/cpi/data.htm

TABLE 2-1. OVERVIEW OF ECONOMIC IMPACT VALUATION MEASURES BY IMPACT CATEGORY

Categories of economic impact grouped by sector. The economic impact measure describes the valuation metric used for each category, and the climate stressors show the climate stressors for which impacts were modeled.

SECTOR	IMPACT CATEGORY	ECONOMIC IMPACT MEASURE	CLIMATE STRESSOR			
			TEMPER-ATURE	PRECIP-ITATION	SLR	STORM SURGE
Natural Resources	Municipal & Industrial / Irrigation Water Supplies	Lost Revenue: Crop sales	🟧	🟩		
	Water Quality – Runoff, Water Temperature	Welfare: Willingness to pay	🟧	🟩		
	Invasive Plant Species	Direct Expense: Invasive species management costs	🟧	🟩		
	Native Plant Species[a]	Not estimated				
	Ecosystem Services	Welfare: Ecosystem services loss			🟦	
	Water Quality – Waste Treatment	Direct Expense: Repair and replacement cost			🟦	🟦
	Water Quality – Contaminated Soil	Direct Expense: Remediation cost			🟦	🟦
Health	Heat Related Mortality and Morbidity	Welfare: Fatal risk, Direct Expense: Cost of hospitalization	🟧			
	Lung and Respiratory Disease	Welfare: Fatal risk	🟧	🟩		
	Allergens and Mold	Direct Expense: Cost of hospitalization	🟧	🟩		
	Vector-Borne Disease	Welfare: Fatal risk, Direct Expense: Cost of illness	🟧	🟩		
Transport-ation	Roads, Rail, and Bridges	Direct Expense: Repair costs, Delay costs	🟧	🟩		
	High and Significant Hazard Dams	Direct Expense: Structural damage	b	🟩		
	Culvert Damage and Road Closures	Direct Expense: Repair costs, Delay costs	b	🟩		
	Coastal Flooding Road Closures	Delay costs			🟦	🟦
Agriculture	Saltwater Intrusion and Inundation on Cropland	Lost Revenue: Crop sales			🟦	🟦
	Crop Growth	Lost Revenue: Crop sales	🟧	🟩		
	Irrigation Needs	Direct Expense: Energy cost of irrigation pumping	🟧	🟩		
	Agricultural Labor	Lost Revenue: Lost wages	🟧			
	Invasive Plant Species on Cropland	Direct Expense: Invasive species management costs	🟧	🟩		
	Milk Production	Lost Revenue	🟧			
	Poultry Heating and Cooling	Direct Expense: Heating and cooling costs	🟧			
Public Safety	Emergency Services Response Times	Welfare: Fatal risk, Direct Expense: Structural damage	🟧	🟩	🟦	🟦
	Access and Upkeep of Evacuation Routes	Welfare: Fatal risk				🟦
	Frequency of Emergency Responses	Direct Expense: Cost of emergency response call	b	🟩		
	Limited Access to Cooling Centers	Welfare: Fatal risk	🟧			

Notes:

a. Economic impacts related to native species were part of the original scope of this analysis; however, they are only discussed qualitatively in this report, due to insufficient information available to monetize impacts reliably.

b. These impact categories are primarily influenced by precipitation however temperature plays a relatively small role in flooding intensity.

2.2 CLIMATE SCENARIOS AND DATA

This analysis considers the impacts of temperature change, precipitation pattern change, and sea level rise (SLR). Below we describe the data sources used for each climate stressor projection.

We consider two future emissions scenarios, namely RCP4.5 (lower emissions) and RCP8.5 (higher emissions).[11] RCPs are scenarios that include a time series of emissions and concentrations for CO_2 and all other greenhouse gases. As described further below, we evaluate multiple variants of global climate models, also known as General Circulation Models (GCMs) and present the average outcome across these models. SLR impacts are evaluated for one SLR projection through to the end of the century, consistent with the 2017 study, *Recommendation of Sea-Level Rise Planning Scenarios for Delaware: Technical Report.* This single SLR trajectory projects 0.75 ft of sea level increase at near century, 1.5 ft at mid-century, and 3 ft at late century, as compared to 2000 levels.[12] A previous study developed approximate RCP-equivalent SLR projections; the SLR projection used in this analysis falls between the SLR projection associated with the RCP4.5 and RCP8.5 emission scenarios.[13] This can be helpful context for comparing results between impact categories where economic impacts are driven by temperature and precipitation changes and those impact categories where economic impacts are driven by SLR. Storm surge impacts are measured for two percentages of occurrence, commonly called return periods: the 1-percent and 10-percent storms. The percentages represent the likelihood that a storm of the given magnitude will occur in a single year, under current climate conditions, but taking future SLR into account.

TEMPERATURE AND PRECIPITATION

We use a suite of GCMs from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) to look at temperature and precipitation under two emissions scenarios: RCP4.5 and RCP8.5. Specifically, we rely on six GCMs from the Localized Constructed Analogues (LOCA) dataset for downscaled and bias corrected projections of the CMIP5 GCMs.[14] While most of the impact category analyses conducted make use of the full set of six GCMs, several impact categories use five GCMs. Our air quality-related analyses uses only two GCMs, due to limitations in results available from the underlying literature and impact models. Temperature and precipitation changes are measured relative to a baseline era defined as 1986-2005.

As these projections come from a different source than those used in the 2014 Delaware Climate Change Impact Assessment, we compare the projections from the LOCA ensemble of GCMs to the projections used in the 2014 assessment. Although there are differences between the DNREC and LOCA ranges, the comparisons are favorable overall. Generally, the maximum positive changes in precipitation are slightly higher under LOCA, and DNREC shows larger maximum

---

[11] RCPs are Representative Concentration Pathways, from work by the Intergovernmental Panel on Climate Change (IPCC). The RCPs are identified by their approximate total radiative forcing (not emissions) in the year 2100, relative to the year 1750: 2.6 W/m2 (RCP2.6), 4.5 W/m2 (RCP4.5), 6.0 W/m2 (RCP6.0), and 8.5 W/m2 (RCP8.5). RCP8.5 implies a future with continued high emissions growth with limited efforts to reduce greenhouse gas emissions, whereas the other RCPs represent mitigation pathways of varying stringency; none of these scenarios represent any particular national or global policy.

[12] Delaware Sea-Level Rise Technical Committee. 2017. Recommendation of Sea-Level Rise Planning Scenarios for Delaware: Technical Report. Available at https://www.dgs.udel.edu/sites/default/files/projects-docs/Delaware%20SLR%20Technical%20Report%202017.pdf

[13] Kopp R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, C. 58 Tebaldi, 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge 59 sites. Earth's Future, 2: 383–406. doi:10.1002/2014EF000239

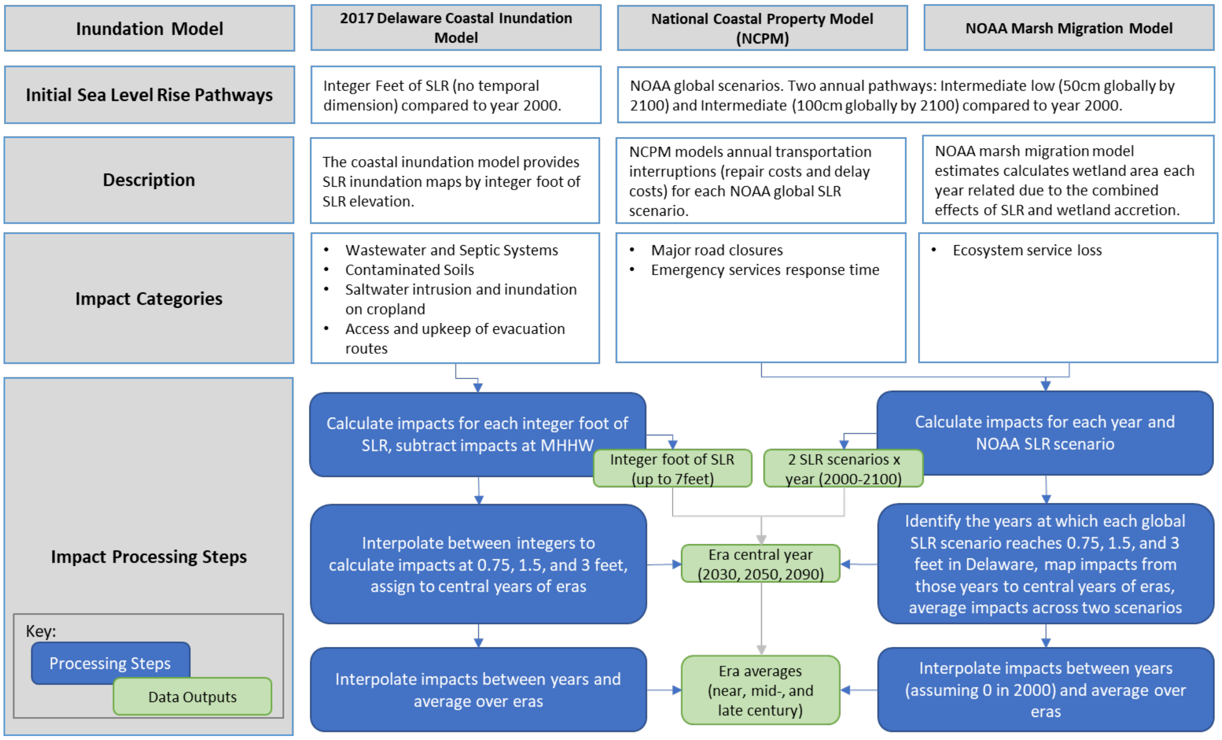
[14] See Appendix B for more details on the climate data used in this analysis.

negative precipitation changes. Further discussion of the LOCA climate data and the comparison to earlier estimates for the state of Delaware is available in Appendix B.

SEA LEVEL RISE

All analyses involving SLR are analyzed for the same SLR projection pathway defined earlier in this section: a projected 0.75 ft increase in sea level by 2030, 1.5 ft by 2050, and 3.0 ft by 2090, compared to 2000 levels. Although we focus on one SLR projection, we utilize three sources of inundation mapping: the 2017 Delaware Coastal Inundation Model,[15] the National Coastal Property Model,[16] and the National Oceanic and Atmospheric Administration (NOAA) Marsh Migration Model.[17] Each model includes particular characteristics or modeling specifications that make it more relevant for specific impact categories, but it is also important to note they produce results consistent with each other, as described below and in **Figure 2-1**.

FIGURE 2-1. SEA LEVEL RISE DATA SOURCES AND PROCESSING STEPS



Inundation Model	2017 Delaware Coastal Inundation Model	National Coastal Property Model (NCPM)	NOAA Marsh Migration Model
Initial Sea Level Rise Pathways	Integer Feet of SLR (no temporal dimension) compared to year 2000.	NOAA global scenarios. Two annual pathways: Intermediate low (50cm globally by 2100) and Intermediate (100cm globally by 2100) compared to year 2000.	
Description	The coastal inundation model provides SLR inundation maps by integer foot of SLR elevation.	NCPM models annual transportation interruptions (repair costs and delay costs) for each NOAA global SLR scenario.	NOAA marsh migration model estimates calculates wetland area each year related due to the combined effects of SLR and wetland accretion.
Impact Categories	• Wastewater and Septic Systems • Contaminated Soils • Saltwater intrusion and inundation on cropland • Access and upkeep of evacuation routes	• Major road closures • Emergency services response time	• Ecosystem service loss

The Delaware Coastal Inundation Model estimates inundation zones for coastal flooding from SLR at one-foot increments from the mean higher high water to this same level plus seven feet. From this, we extract the 0.75 ft, 1.5 ft, 3 ft and storm surge elevations to assess resources at risk of inundation (as sea levels rise) and temporary flooding (from high tide floods or periodic storm surge).

---

[15] https://www.dgs.udel.edu/projects/coastal-inundation-maps-delaware

[16] See Mark Lorie, James E. Neumann, Marcus C. Sarofim, Russell Jones, Radley M. Horton, Robert E. Kopp, Charles Fant, Cameron Wobus, Jeremy Martinich, Megan O'Grady, Lauren E. Gentile. 2020. Modeling coastal flood risk and adaptation response under future climate conditions. Climate Risk Management 29 https://doi.org/10.1016/j.crm.2020.100233

[17] https://coast.noaa.gov/digitalcoast/tools/slr.html

The National Coastal Property Model and the NOAA Marsh Migration Model incorporate annual local SLR elevations through the 21st century, corresponding to six NOAA global scenarios (30, 50, 100, 150, 200, and 250 cm globally). We only use the results for the Intermediate-Low (50 cm) and Intermediate (100 cm) global scenarios, as those project SLR most consistently with the SLR timing of the projection pathway used in this study. **Table 2-3** shows that the SLR associated with the projection used in this study typically falls somewhere between the SLR associated with the two selected NOAA scenarios. For instance, this report assumes a projected 1.5 ft increase in sea level by 2050, while the Intermediate-Low and Intermediate NOAA scenarios predict this level of SLR by 2058 and 2041 respectively. Impacts in each era are calculated as the average impacts modeled by each of the two selected NOAA scenarios, each using 11-year windows around the arrival times for each height identified in our pathway. For example, 2030 impacts are calculated as the average across modeled impacts from the Intermediate-Low scenario (annual average, 2025-2035) and Intermediate scenario (annual average 2017-2027). Late century impacts are defined only using the Intermediate scenario as the Intermediate-Low scenario does not reach 3.0 feet of SLR by 2100.

TABLE 2-3. ARRIVAL YEARS FOR DELAWARE SLR HEIGHTS IN NOAA GLOBAL SCENARIOS

DELAWARE SLR HEIGHTS AND ARRIVAL YEARS		ARRIVAL YEARS BY NOAA GLOBAL SLR SCENARIO (2000-2100)					
YEAR	FT	LOW	INTERMEDIATE -LOW	INTERMEDIATE	INTERMEDIATE -HIGH	HIGH	EXTREME
2030	0.75	2032	2030	2022	2018	2015	2015
2050	1.5	2064	2058	2041	2033	2029	2027
2090	3.0	-	-	2070	2056	2048	2044

Note: The Low and Intermediate-Low scenarios do not reach 3 ft of SLR by the end of the century. These scenarios are shaded in green.

The National Coastal Property Model provides a "bathtub" modeling capability to estimate storm surge elevations above sea level by county for various return periods — we use the 1- and 10-percent events, signifying the probability that an event of that magnitude occurs in a given year.[18] Such a bathtub model approach assumes that as sea levels rise, flood elevations rise at the same rate, as in a bathtub, but only if potentially inundated area and coastal waters are connected via the surface hydrology.

The NOAA Marsh Migration model includes multiple sediment accretion rate assumptions, as well, and also uses a bathtub approach. Accretion rates are important for estimating land use change and for modeling wetland migration. The NOAA Marsh Migration model also incorporates a "mask" for currently developed areas, an area where the model prevents wetlands from migrating, reflecting the reasonable assumption that landowners will not abandon developed areas to allow wetlands to migrate to current upland areas.

---

[18] These are also sometimes referred to as 10-year and 100-year events. We use the probability notation throughout this report. The bathtub model approach used here incorporates a hydrologic connectivity constraint — that is, areas at a particular elevation are flooded only if both the elevation is below the sea level or flood level and if there is a surface hydrology connection to the coastal source of the flood water.

STORM SURGE

The magnitudes of the 1-percent and 10-percent storms were derived using historical tide gauge measurements[19] for the two stations in Delaware with sufficient lengths of record—namely, the gauges near Reedy Point (for New Castle and Kent Counties) and Lewes (for Sussex County).[20] While storm surge probabilities and heights are likely to change in the future due to climate change (e.g., because warmer oceans may increase the intensity of storms in the future), estimating future storm surge probabilities and heights is highly uncertain[21] and was not attempted in this work. As such, this means that the magnitude of the 1-percent and 10-percent storm are treated as fixed over the course of the century and are representative of *the current climate.* However, the analysis of storm surge impacts still captures some degree of climate change because the analysis does account for SLR, and the total area inundated during storm surges increases over time as the sea level rises.[22]

To calculate storm surge damages from the 1-percent and 10-percent storms, we first identify the assets that fall within the storm surge inundation area but outside of the area flooded by SLR in 2030, 2050, and 2090. This allows us to differentiate between the assets affected by the storm surge event versus those already inundated by SLR. We identify assets within the storm surge inundation area following the same process outlined in **Figure 2-1**, but instead of evaluating the damages for the various SLR heights in each era (i.e., 0.75, 1.5, and 3.0 ft), we evaluate the damages for the different county-specific storm surge heights, shown in **Table 2-4**.

All storm surge impacts estimated in this way are not represented as annual damages but rather as damages per storm surge event. As previously described in Chapter 1.2, the conversion of per event damages to expected annual damages requires information on additional storm return intervals beyond just the 1-percent and 10-percent storms considered in this work.

Comparisons of current and future storm surge economic impacts can also be complicated by the possibility that, after storm surge damage, some assets may be moved away from risky locations or abandoned in future periods. Estimating the movement or abandonment of assets in the future, in response to climate change risks or for other reasons, is beyond the scope of this report. Therefore, we assumed that assets remain in place through to the end of the century.

---

[19] NOAA (National Oceanic and Atmospheric Administration) Water Levels. Available at https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels [Accessed 2019]

[20] Using these tide gages, we extracted the maximum daily water level from each record and de-trended the resulting set of maximum gauge heights from each time series. From the detrended data, we then calculated a distribution of storm surge heights by fitting a generalized extreme value distribution to the annual maximum time series from each gauge. These represent historical surge heights.

[21] More detail here: Lorie, Mark, James Neumann, Marcus Sarofim (corresponding), Russell Jones, Radley Horton, Robert E. Kopp, Charles Fant, Cameron Wobus, Jeremy Martinich, Megan O'Grady, 2019, Modeling Coastal Flood Risk and Adaptation Choices under Future Climate Conditions, Climate Risk Management 29 https://doi.org/10.1016/j.crm.2020.100233

[22] Note that for the impact categories affected by storm surge, inundation from SLR differ from the impact of storm surge flooding. Therefore, in most cases storm surge damages decline over the century as more of the vulnerable assets concentrated along the coast fall within the SLR inundation zone, while the storm surge inundation zone moves beyond the area of concentrated infrastructure. This is likely to be counteracted by increased development inland as sea level rises. However, however this inland migration is outside of the scope of this analysis. High tide flooding in an exception, where storm surge impacts also include episodic events within the SLR inundation zone.

TABLE 2-4. SEA LEVEL RISE AND STORM SURGE HEIGHTS (FEET)

Sea level elevations, in feet, above the year 2000 mean higher high water, for 10- and 1-percent storm events (measured by NOAA tide gauges) during three future eras, by county.

	NEAR CENTURY (0.75 FT SLR)		MID-CENTURY (1.5 FT SLR)		LATE CENTURY (3.0 FT SLR)	
	SLR + 10% STORM	SLR + 1% STORM	SLR + 10% STORM	SLR + 1% STORM	SLR + 10% STORM	SLR + 1% STORM
Kent County	3.427	4.089	4.177	4.839	5.677	6.339
New Castle County	3.344	4.314	4.094	5.064	5.594	6.564
Sussex County	4.337	6.652	5.087	7.402	6.587	8.902
Notes: SLR + storm surge heights are capped at 7 ft in the analysis due to data availability (capping applied to the scenarios highlighted in orange). The term “mean higher high water” is a technical expression representing the average height of the highest tide recorded at a tide station for the subject year. It is used here, and in NOAA technical analyses of climate change, as a common base datum from which to measure future SLR.						

HURRICANE AND STORM SURGE EVENT FREQUENCY

In two analyses, for mold-related disease (Chapter 4.3) and the frequency of emergency response (Chapter 7.3), the analysis requires a discrete hurricane or storm surge event frequency projection to estimate future disease or injury incidence. For those analyses only we use a study which projects the frequency of a 1 percent hurricane storm surge event, only for the late century period.[23] Because those results are limited to the 1 percent event, and to a single time period (late century), we do not use that study in other storm surge flood analyses in this report. Unlike other storm surge analyses, the event-based frequency estimate allows us to generate a scalar for hurricane frequency that is applied to the baseline annual disease or injury incidence, resulting in an annual projected estimate of disease or injury for future periods. As stated above, other analyses rely on flood mapping of storm surge and which at this time cannot be adjusted for the full range of flood events across all return periods. When we apply the event-based study, the late century frequency result is interpolated linearly to the near and mid-century periods.

---

[23] Marsooli, R., Lin, N., Emanuel, K. and Feng, K. 2019. Climate change exacerbates hurricane flood hazards along U.S. Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications. 10, 3785.

CHAPTER 3 | NATURAL RESOURCES IMPACTS (DNREC)

The Delaware Department of Natural Resources and Environmental Control (DNREC) plays an important role in managing the state's natural resources and engaging the public in resource stewardship. Understanding how climate change may affect the state's resources will assist DNREC in effectively preserving, protecting, or maintaining Delaware's natural assets for the future. Climate change is likely to affect various aspects of the natural resource sector, including:

1. **Municipal, industrial, and irrigation water supplies**, from both surface water and groundwater, during peak water usage in the summer.
2. **Water quality changes** due to increased average precipitation and heavy rainfall events that produce runoff, as well as from increased water temperatures.
3. **Native plant species survival and reproduction** during extended high heat events, extreme weather, and prolonged drought.
4. **The spread of invasive plant species** in forest, beach and dune, and wetland and aquatic ecosystems.
5. **Loss of forest, beach and dune, and wetland and aquatic ecosystems** in relation to the ecosystem services they provide for water quality, flooding and storm surge, and habitat for commercially valuable species.
6. **Water quality due to sea level rise (SLR) impacts** on public/privately-owned municipal wastewater treatment.
7. **Contaminated soils and water quality**, if current and historic industrial and/or brownfield areas flood under predicted SLR scenarios.

Table 3-1 presents annual statewide impacts by category. Impacts in this sector are primarily driven by lost welfare value (through water quality impacts and ecosystem service losses), the combined impacts of which total over half a billion dollars per year by the end of the century (under RCP8.5, which is the higher of the two emissions scenarios considered in this analysis; Chapter 2.1 provides further details on these emissions scenarios).

TABLE 3-1. ANNUAL STATEWIDE ECONOMIC IMPACTS TO NATURAL RESOURCE CATEGORIES ($MILLION)

Figures represent total statewide impacts by RCP (for categories impacted by changes in temperature and precipitation) or by era only (for categories impacted by SLR, excluding storm surge) in millions of dollars (2019). As this table presents annual impacts, storm surge impacts are not included, as such impacts are estimated on a per-event basis. For further information on each category, please see Chapters 3.1 through 3.7.

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
3.1	Public and agricultural water supplies	<$0.001	<$0.001	<$0.001	<$0.001	$0.028	-$0.008
3.2	Water quality from changes in climate	$93	$77	$150	$120	$360	$210
3.3	Native plant species survival and reproduction[a]	-					
3.4	The spread of invasive plant species	$0.15	$0.15	$0.24	$0.24	$0.32	$0.29
3.5	Loss of forest, beach and dune, and wetland and aquatic ecosystems[b]	$55		$80		$160	
3.6	Water quality due to SLR impacts	$0.20		$0.50		$0.62	
3.7	Contaminated soils and water quality	$1.4		$1.2		$1.0	

Notes: a. Native plant species are discussed qualitatively, due to limited availability of necessary data, in Chapter 3.3.
b. Damages based on a 4mm/year sediment accretion rate.

Figure 3-1 shows the distribution of annual impacts by county. While the total impacts increase over the course of the century, New Castle and Sussex counties consistently account for a similar proportion of the impacts, while impacts in Kent County are consistently about half those seen in the other two counties.

FIGURE 3-1. NATURAL RESOURCE ECONOMIC IMPACTS BY COUNTY

Totals represent temperature and precipitation-based impacts (RCP8.5 or RCP4.5) plus SLR impacts. As this figure presents annual impact values, totals do not include storm surge impacts, as such impacts are estimated on a per-event basis. Values are reported in 2019 dollars.

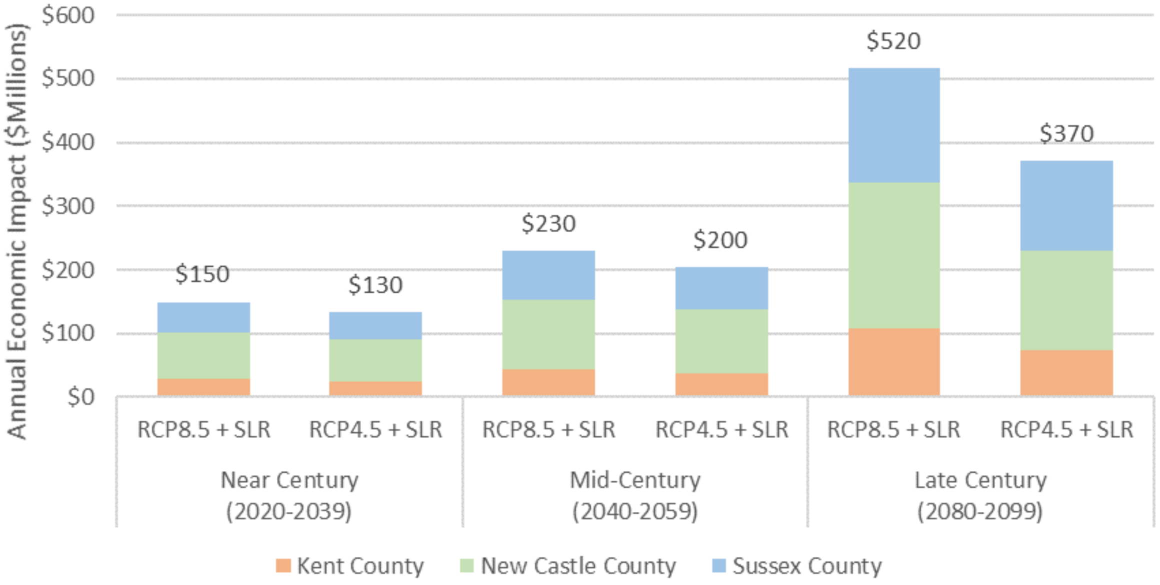


Table 3-2 shows impacts related to storm surge events on natural resources, specifically for the water quality (waste treatment) and contaminated soil flooding categories. Storm surge damages, particularly as related to contaminated soil flooding, may cause significant impacts.

TABLE 3-2. STATEWIDE ECONOMIC IMPACTS TO NATURAL RESOURCE CATEGORIES FROM STORM SURGE EVENTS ($MILLION)

Impacts shown below result from 1-percent and 10-percent storm surge events, reported in millions of dollars (2019). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The below values represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year).

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		10% Storm	1% Storm	10% Storm	1% Storm	10% Storm	1% Storm
3.6	Water Quality, Waste Treatment	$8.9	$15	$10	$14	$8.4	$8.4
3.7	Contaminated Soil Flooding	$56	$68	$63	$71	$54	$61

3.1 MUNICIPAL, INDUSTRIAL, AND IRRIGATION WATER SUPPLIES

Municipal, industrial, and irrigation water supply, from both surface water and groundwater

Under climate change, there is general agreement among General Circulation Models (GCMs) that the northeastern U.S. will become wetter on average. However, summer rainfall is likely to decrease and become more variable, while irrigation water demand is likely to increase as crop evapotranspiration rises under warming conditions. As a result, municipal, industrial, and irrigation water supplies may be threatened, particularly during days of peak summer water demand.

Methods:

We estimate the impacts of unavailable water supplies for two water user groups:

a. **Municipal and industrial water supply:** reductions in water supplied to both municipal and industrial users are monetized by estimating welfare losses.[24] Municipal and industrial water users typically hold a value for water above the price they pay for water. The value held above the price is known as "consumer surplus", which is a measure of economic welfare. When the water supply does not meet users' demand, users miss out on the surplus they would have received if they could consume the full amount of water demanded. Welfare losses are therefore defined as the quantity of unmet demand multiplied by the difference between water prices and the users' value for water.

b. **Irrigation water supply:** reductions in water supply for irrigated crops were monetized by taking the difference between fully irrigated production and partially irrigated production and converting these to reduced crop revenues.[25]

To estimate municipal, industrial and irrigation water shortages over time due to climate change, we rely on outputs from a water systems model called U.S. Basins that IEc has developed and applied in several U.S. EPA studies.[26] The model has a spatial resolution of over 2000 eight-digit hydrologic unit code (HUC) basins across the contiguous U.S., eight of which are partially or wholly in Delaware. We use a scenario-based approach, where future climate change scenarios are compared to a "control" scenario that includes population growth while maintaining historical climate conditions. With this approach, we isolate the impacts of population growth from climate change effects.

This water systems model balances river runoff and water demands within reservoirs in each basin (which are networked in upstream-downstream relationships based on the U.S. river system) and provides information on unmet municipal, industrial and agricultural water demands

---

[24] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001, Chapter 5, Extreme Heat Mortality.

[25] U.S. Department of Agriculture National Agriculture Statistics Service, using the average of available values for 2007 to 2019, https://www.nass.usda.gov/Data_and_Statistics/

[26] Boehlert, B., Strzepek, K. M., Chapra, S. C., Fant, C., Gebretsadik, Y., Lickley, M., Swanson, R., McCluskey, A., Neumann, J. E. and Martinich, J. 2015, Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *J. Adv. Model. Earth Syst.*. doi:10.1002/2014MS000400.

within each basin under a range of climate change scenarios through 2100.[27] For this analysis, we import the fraction of agricultural, municipal, and industrial demands that are unmet for the Delaware basins under each climate scenario and extract the impacts to irrigated crops and municipal and industrial water users. Within the eight basins of Delaware, we weight these unmet demand percentages by population and irrigated land area to generate statewide estimates of unmet demand.

Municipal and industrial water supply

This analysis estimates the welfare loss to consumers due to water shortages from climate change. To develop these estimates, the analysis defines demand functions for three categories of municipal and industrial water demand: municipal indoor use, municipal outdoor use, and industrial use.[28] Welfare losses are calculated for each eight-digit HUC using the approach described in EPA (2017).[29] Welfare change is estimated using municipal and industrial water supply prices from over 300 utilities nationwide. Although none of these reporting utilities are in the state of Delaware, 20 of the utilities are in bordering states. Prices are based on the nearest reporting utility to each eight-digit HUC. Welfare loss estimates due to climate change for each scenario are calculated as the difference in welfare loss between the control and climate scenario, summed across the three demand categories.

Irrigation water supply

When famers are unable to fully irrigate crops due to water shortages, yields of irrigated crops decline to a level less than fully irrigated yields but typically still higher than rainfed yields. We monetize the effects of water shortages for irrigated crops as a reduction in yield, resulting in a loss in revenue. Baseline revenues are based on the U.S. Department of Agriculture National Agriculture Statistics Service, averaged over the available values from 2007 to 2019. To estimate the reduction in yields when crops are only partially irrigated during water shortages, we use the equations provided in the Food and Agriculture Organization's Drainage Paper No. 56.[30] This approach uses a water-driven model of crop growth, which is ideal for estimating water shortage impacts on crop yields, with a total of 33 crops modeled in U.S. Basins. The main irrigated crops in Delaware (corn, soybeans, barley, hay, and wheat) are included, with total irrigated areas, as part of the U.S. Basins model. Since the objective is to value water shortages to irrigated crops, we assume water shortage is the primary cause of losses in yield and, as a result, losses in crop revenue.[31]

Table 3-3 lists those data sources used in this analysis that are not part of the U.S. Basins model.

---

[27] See the following for more details: Boehlert, B., Strzepek, K. M., Chapra, S. C., Fant, C., Gebretsadik, Y., Lickley, M., Swanson, R., McCluskey, A., Neumann, J. E. and Martinich, J. 2015, Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *J. Adv. Model. Earth Syst.*. doi:10.1002/2014MS000400.

[28] Based on data collected in the U.S. Geological Survey's National Water-Use Science Project. U.S. Geological Survey, cited 2017: The National Water-Use Science Project. Available online at http://water.usgs.gov/watuse/wunwup.html

[29] U.S. Department of Agriculture National Agriculture Statistics Service, using the average of available values for 2007 to 2019, https://www.nass.usda.gov/Data_and_Statistics/

[30] Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. FAO Irrigation and Drainage Paper No. 56. Rome: Food and Agriculture Organization of the United Nations, 1998.

[31] Note that this category of impacts addresses the same impacts described in Chapter 6.3. Here, we assume no additional pumping is undertaken and therefore the damage is measured as loss of yield. In Chapter 6.3, we assume farmers increase pumping to avoid yield losses. These are two reasonable approaches to the same issue but serve as alternative estimates of the same damage and should not be summed.

TABLE 3-3. WATER SUPPLIES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Water supply prices	Municipal and industrial water supply prices from over 300 utilities nationwide	American Water Works Association and Raftelis Financial Consultants, 2015. 2014 Water and Wastewater Rate Survey.
Crop sales	Delaware county-specific crop sales	U.S. Department of Agriculture National Agriculture Statistics Service, average of available values for 2007 to 2019. https://www.nass.usda.gov/Data_and_Statistics/

Results:

Municipal and Industrial Water Supply

In the eight-digit HUCs that overlap with the state of Delaware, there are no municipal and industrial water shortages identified under any scenario. This result is due to the overall increase in precipitation expected in most scenarios and due to the assumption that municipal and industrial water users have priority access to water supplies in the U.S. Basins model.

Irrigated crops

According to the U.S. Department of Agriculture, about 53 percent of the total area of corn, soybeans, barley, hay, and wheat in Delaware is irrigated.[32] Of this irrigated area, about 46 percent resides in Sussex County, 38 percent in Kent County, and only 16 percent in New Castle County. Average total sales of these five crops in Delaware amounts to $128 million per year, averaged over 2007-2019, according to the U.S. Department of Agriculture.

Table 3-4 shows the total losses in revenue of irrigated crops for the three counties under the two different RCPs. These costs are the average values produced by five different GCMs and represent a deviation from the control scenario, which uses historical climate conditions from 1986-2005. Based on the model output, unsupplied water demands in Delaware are rare and will continue to be rare in the future, resulting in very minor impacts to crop sales (note that the values in **Table 3-4** are in dollars per year). Even in the late century, where impacts are the highest, sales losses are predicted to be only 0.02 percent of total sales. While the majority of the revenues for irrigated crops are in Sussex County, the majority of the damages and benefits (negative damages) will be incurred in Kent County. Some scenarios suggest that there may be more water in future eras resulting in benefits (negative damages) to water availability — meaning a reduction of impacts from constrained water availability on baseline yields.

---

[32] U.S. Department of Agriculture National Agriculture Statistics Service, using the average of available values for 2007 to 2019, https://www.nass.usda.gov/Data_and_Statistics/

TABLE 3-4. ANNUAL ECONOMIC IMPACTS TO IRRIGATED CROPS FROM CLIMATE CHANGE

Impacts are defined as lost irrigated crop sales relative to a 2007-2019 historical mean crop revenue and the baseline climate scenario (1986-2005), measured in dollars (2019) per year and averaged over 5 GCMs. Irrigated crops include corn, soybeans, barley, hay, and wheat. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	<$1,000	<$1,000	<$1,000	<$1,000	$28,000	-$9,100
New Castle County	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000
Sussex County	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000	$1,000
Delaware Total	**<$1,000**	**<$1,000**	**<$1,000**	**<$1,000**	**$28,000**	**-$8,000**

Note: Positive values indicate damages, while negative values in this table represent reductions in damages (i.e., benefits) relative to the modeled baseline period damages.

Limitations:

- The U.S. Basins model evaluates water allocation using a monthly time step over large, aggregated areas (eight-digit HUCs). Our drought impact model is limited to seasonal time scales rather than short-term water supply deficits (e.g., days or weeks), which often happen at smaller spatial scales. Since Delaware has a relatively humid climate, with available water storage in both surface reservoirs and groundwater, short-lived droughts (intra-monthly) may not be a statewide concern.
- Harvested areas and crop types are assumed to remain constant throughout the century. These may change due to a variety of factors including federal and state subsidies or saltwater intrusion from SLR.
- Our analysis assumes farmers grow the same crop mix in the future as in the past, however farmers could change their crop mix in the future, switching for example, to more or less water-intensive crops.

3.2 WATER QUALITY DUE TO CHANGES IN RUNOFF AND WATER TEMPERATURE

Water quality changes from the impacts of increased average precipitation and heavy rainfall events that produce runoff, as well as changes from increased water temperatures

Changes in precipitation patterns and air temperature affect water quality. Increases in precipitation, particularly heavy rainfall, carry nutrient pollution to water bodies, potentially altering ecosystem balance. In addition, warmer temperatures increase chemical reaction rates, lower dissolved oxygen saturation levels, and adversely affect algal competition, increasing the chance of harmful algal blooms.

Methods:

This analysis transfers results from two IEc analyses conducted for the U.S. EPA on the economic consequences of climate change on water quality: a model of general water quality impacts and a model that focuses on the risks of harmful algal blooms. The socioeconomic data used in this analysis is summarized in **Table 3-5**.

TABLE 3-5. WATER QUALITY ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Willingness to pay for water quality improvements	User and non-user willingness to pay for water quality improvements, based on 131 estimates from 18 studies that were used to construct a meta-regression analysis nationwide	Van Houtven, G., Powers, J. and Pattanayak, S. K. 2007. Valuing water quality improvements in the United States using meta-analysis: Is the glass half-full or half-empty for national policy analysis? Resource and Energy Economics, 29, 206-228.
Recreation use values database for North America	Daily use values for common recreation activities reported on public lands, from studies conducted from 1958 to 2006	Rosenberger, R.S. 2016. Recreation Use Values Bibliography: 1958-2015. Corvallis, OR: Oregon State University, College of Forestry. 33p.
Recreational visitation to state parks with waterbodies	Annual visitation for four Delaware state parks with recreational waterbodies in 2019	DNREC, Division of Parks and Recreation.

Water Quality (General)

The U.S. Basins water quality model[33] builds on the structure of the U.S. Basins water systems model, and is run across more than 2000 HUCs of the contiguous U.S. The analyses evaluated how changing temperature and precipitation patterns would affect nutrient runoff, water temperature, and dissolved oxygen concentrations. These were used to estimate changes in a water quality index that was linked to a willingness to pay to maintain historical water quality

---

[33] Boehlert, B., Strzepek, K. M., Chapra, S. C., Fant, C., Gebretsadik, Y., Lickley, M., Swanson, R., McCluskey, A., Neumann, J. E. and Martinich, J. 2015, Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *J. Adv. Model. Earth Syst.*. doi:10.1002/2014MS000400.

levels.[34] Willingness to pay values are unique for each of the U.S. EPA's Level III Ecoregions,[35] with the state of Delaware located entirely in the Mid-Atlantic Coastal Ecoregion. Willingness to pay is a per person, per year value. To get the total annual costs by county, these values are multiplied by the adult population (18+) of each county. Outputs from the model are reported at the HUC-level and aggregated to the three counties in Delaware for this report. We use the latest results of the model, as documented in Fant et al. (2017).

Harmful Algal Blooms

Chapra et al. (2017) added a module to the U.S. Basins water quality model to simulate competition between algal groups.[36] They focused on cyanobacteria growth and the likelihood of Cyano harmful algal blooms in freshwater systems for two growth scenarios — high and low growth — which provides an uncertainty range on the change in Cyano harmful algal blooms growth patterns as temperatures rise. We use an average of the two growth scenarios to provide a central estimate of the impacts. When Cyano harmful algal blooms release toxins, it can have various adverse health impacts to people and other mammals, such as pets. However, this analysis focuses on potential recreational waterbody closures only. Harmful algal blooms results are scaled based on visitor use totals at four state parks that contain recreational waterbodies (Bellevue, Lums Pond, Killens Pond, and Trap Pond), as provided by the DNREC Division of Parks and Recreation.[37]

The impacts on recreational activity are based on thresholds defined by World Health Organization guidelines[38] for evaluating recreational restrictions attributable to harmful algal blooms. The World Health Organization recommendations for harmful algal bloom thresholds establish 20,000 cells/ml for some populations experiencing allergic effects and 100,000 cells/ml where recreational restrictions would be advised for the general population. In these analyses, we use the 100,000 cells/ml threshold to quantify the number of days in each month where the concentration of harmful algal blooms is projected to be equal to, or greater than, this threshold for each park's waterbody. We assume that this reflects the number of lost visitor-days at each of the four parks. The value of each visitor-day is based on daily recreation use values for common recreation activities, reported in public land studies.[39] These recreation use value estimates are measures of individual willingness to pay to participate in certain recreational activities, based on 421 economic valuation studies in the U.S from 1958 to 2015. Since none of the public lands included in these past studies were located in Delaware, or its bordering states, we use the national average of $37.30 per visitor-day. **Table 3-6** shows the four waterbodies evaluated and the baseline visits per year, based on 2019 visitation data from Delaware State Parks. For future

---

[34] From Van Houtven, G.; Powers, J.; Pattanayak, S. K. Valuing water quality improvements in the United States using meta-analysis: Is the glass half-full or half-empty for national policy analysis? Resource and Energy Economics, 2007, 29, 206-228. For this specific application, see Fant, C., R. Srinivasan, B. Boehlert, L. Rennels, S. C. Chapra, K. M. Strzepek, J. Corona, A. Allen, J. Martinich. Climate Change Impacts on U.S. Water Quality using two Models: HAWQS and US Basins. Water 2017, 9(2), 118; https://doi.org/10.3390/w9020118 for more details.

[35] For maps and description of these, see https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states

[36] Chapra, S. C.; B. Boehlert, C., Fant; J. Henderson, D. Mills, D. M.L. Mas, L. Rennels, L. Jantarasami, J. Martinich, K. M. Strzepek, V. J. Bierman, Jr., H. W. Paerl. Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwater. Environ. Sci. Technol., 2017, 51 (16), pp 8933–8943. DOI: 10.1021/acs.est.7b01498

[37] Through personal communication

[38] World Health Organization. Toxic Cyanobacteria in Water: A guide to their Public Health Consequences, Monitoring and Management; E & FN Spon, 1999: London, http://www.who.int/water_sanitation_health/resourcesquality/toxcyanobacteria.pdf?ua=1

[39] Rosenberger, Randall S. 2016. Recreation Use Values Bibliography: 1958-2015. Corvallis, OR: Oregon State University, College of Forestry. 33p.

periods, we assume that these visits grow along with population. Based on the limited number of waterbodies with monthly visitation data in the Eastern U.S., we assume that 75 percent of annual recreational visitation to sites occurs in the summer season from May through September, with the remaining 25 percent of visitation occurring in non-summer months (i.e., October through April). Within these two seasons, we assume visitation is spread evenly for each day. For example, we do not distinguish between a weekday and a weekend in this analysis.

TABLE 3-6. STATE PARK WATERBODIES EVALUATED AND BASELINE VISITS

STATE PARK NAME	COUNTY	VISITS / YEAR
Bellevue	New Castle	316,966
Lums Pond	New Castle	334,911
Killens Pond	Kent	269,566
Trap Pond	Sussex	162,545

Results:

Table 3-7 shows the total annual impact from the degradation of water quality caused by changes in climate for the near, mid- and late century, averaged across five different GCMs. The impact of climate is isolated from the effect of population growth by subtracting the control scenario, which includes population growth without climate change. Note that the near century era was not included in the latest results of the U.S. Basins water quality model (as documented in Fant et al., 2017), hence it was estimated using a linear interpolation between the baseline and mid-century willingness-to-pay for both the climate change and control scenarios. The total impacts for Delaware are predicted to be lower under the RCP4.5 scenario than the RCP8.5 scenario, and the emissions mitigation benefit (i.e., the difference between RCP8.5 and RCP4.5) is larger in the late century than the mid-century. Since costs are based on a per person, per year, willingness to pay, impacts are generally higher in counties with larger populations, which is why New Castle County incurs the largest change in impact. Changes in impacts per capita are highest in Sussex County — almost twice as high as in Kent County, which has the lowest per person impact by the late century for RCP8.5, This result is primarily due to higher increases in nutrient concentrations in Sussex County compared to the other two counties.

Table 3-7 also shows the value lost from waterbody closures from Cyano harmful algal blooms for the four parks from **Table 3-6**, aggregated by Delaware's three counties. These are represented by the average value lost as compared to the control scenario. The control scenario uses baseline climate data combined with population growth, across GCMs and average low and high cyanobacteria growth scenarios. Similar to the general water quality impacts shown in **Table 3-7**, we use linear interpolation to estimate the near century cost using the mid-century and baseline estimates. The two parks in New Castle County (Bellevue and Lums Pond) that have the highest visitation rates also have the largest climate change impacts. As a result, the two parks in New Castle County incur 95 percent to 99 percent of the total impacts across all scenarios.

Finally, **Table 3-7** shows the total costs as a result of climate change, including both the general water quality cost based on willingness to pay and recreational impacts from harmful algal blooms. Impacts in New Castle County are projected to be more than double the other two counties in all scenarios. By the late century, costs are predicted to be 70 percent higher under the RCP8.5 emissions scenario than under RCP4.5.

TABLE 3-7. ANNUAL ECONOMIC IMPACTS FROM CHANGES IN WATER QUALITY AS A RESULT OF CLIMATE CHANGE ($MILLION)

Impacts include water quality and harmful algal blooms damages above the baseline climate scenario (1986-2005), measured in millions of dollars (2019) per year and averaged over 5 GCMs. Water quality impacts are based on a per person, per year willingness to pay to maintain historical water quality levels, scaled up to the county level. Harmful algal blooms impacts are measured as recreational value lost, based on daily recreation use values for common recreation activities reported in public land studies conducted from 1958 to 2015. Values may not sum due to rounding.

		NEAR CENTURY (2020-2019)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Water Quality	Kent County	$18.6	$14.1	$29.9	$22.6	$78.9	$44.6
	New Castle County	$43.9	$38.8	$66.6	$58.8	$170.7	$103.8
	Sussex County	$18.4	$13.4	$33.6	$24.4	$89.2	$49.5
	Delaware Total	**$81.0**	**$66.2**	**$130.1**	**$105.8**	**$338.8**	**$197.9**
Harmful Algal Blooms	Kent County	$0.0	$0.0	$0.0	$0.0	$0.2	$0.2
	New Castle County	$11.6	$11.1	$18.3	$17.4	$17.7	$12.1
	Sussex County	$0.2	$0.1	$0.3	$0.2	$0.3	$0.4
	Delaware Total	**$11.8**	**$11.2**	**$18.6**	**$17.5**	**$18.2**	**$12.7**
Water Quality and Harmful Algal Blooms	Kent County	$19	$14	$30	$23	$79	$45
	New Castle County	$56	$50	$85	$76	$190	$120
	Sussex County	$19	$13	$34	$25	$89	$50
	Delaware Total	**$93**	**$77**	**$150**	**$120**	**$360**	**$210**

Limitations:

- The water quality model relies on a complex system of models built to assess climate change impacts at a national or regional scale and are meant to provide a starting point for future, more detailed modeling. For more detail on model-specific limitations and caveats, see Boehlert et al. (2015) and Fant et al. (2017), for the general water quality model, and Chapra et al. (2017) for the harmful algal blooms model.
- Pesticides, herbicides and other hazardous substances are excluded from this analysis but are likely to have impacts on future water quality and natural ecosystems.
- The general water quality valuation is based on a willingness to pay survey of both users and non-users and therefore represents costs from the human perspective. These may not

represent the entire burden of costs, particularly any adverse effects to the surrounding ecosystem.

- The willingness to pay estimates are per person, per year, scaled by population. As such, areas with a lower population have lower annual costs than higher population regions.
- Harmful algal bloom-related costs are limited to what can be valued directly. These only include the costs for waterbodies with visitation data and the national average value of visitor-days. Other waterbodies may be affected as well. In addition, harmful algal blooms can contaminate municipal water supplies if blooms occur near water treatment plant intakes, which may lead to a temporary water shutoff for the supplied community. This, as well as impacts along rivers and streams, are not considered in this valuation.
- Visitation numbers are for the entire park and not just use of the waterbody, but the assumption is that harmful algal blooms will reduce overall park visitation, as the ponds are one of the major draws in the parks.

3.3 NATIVE PLANT SPECIES SURVIVAL AND REPRODUCTION

Native plant species survival and reproduction during extended high heat events, extreme weather, and prolonged drought

As the climate changes and impacts grow more extreme, the regions of Delaware that are suitable for native plant species survival are likely to decline. Due to land use change, invasive species encroachment, and other factors, 40 percent of Delaware's native plant species are threatened or already extirpated from the state.[40] Although few studies have been conducted that evaluate the effect of climate change on native species survival and reproduction (and to our knowledge, none in Delaware), existing research suggest climate change may have dire consequences. For example, Loarie et al. (2008) find that up to two-thirds of California's native species will experience greater than 80 percent reductions in range size within the century.[41]

Insufficient information is readily available to monetize the effects of climate change on native plant species survival and reproduction in Delaware. Here, we briefly illustrate one set of possible analytical steps for such an evaluation, along with data gaps.

Methods:

Below, we outline an approach that relies on bioclimatic envelope modeling, following the process described in the section on invasive species management (Chapter 3.4).[42] A summary of that process tailored to native species is as follows:

1. **Identify the key species of concern and habitat areas.** DNREC provided IEc with a list of 489 species, of which 64 have a designation of S1, meaning they are at high risk because of limited numbers and/or habitat and are thus highly vulnerable to extirpation from the state. To conduct a climate change impact assessment, this list will need to be distilled to a small subset of representative species. Criteria for inclusion of a species can include sensitivity to climate change, representativeness or importance of the species, and data available on the existing range and bioclimatic requirements.
2. **Develop bioclimatic ranges that describe suitable habitat conditions for each species.** To establish suitable habitat for the species, spatial data on existing habitat area and information on bioclimatic requirements are needed. Baseline climate data would be overlain on the areas of existing habitat to define ranges for each bioclimatic requirement that constrain suitable habitat.
3. **Conduct bioclimatic envelope analysis on representative species.** This step uses baseline and projected daily gridded climate data to evaluate whether each of the species' bioclimatic requirements is met across Delaware. The region of suitability defines the bioclimatic envelope for that climate. If climate change causes the envelope to contract, species habitat may be lost.

---

[40] DNREC. 2017. Final Report of the Statewide Ecological Extinction Task Force. Accessed from http://www.dnrec.delaware.gov/Admin/Documents/de-eetf-final-report.pdf

[41] Loarie SR, Carter BE, Hayhoe K, McMahon S, Moe R, et al. (2008) Climate Change and the Future of California's Endemic Flora. PLoS ONE 3(6): e2502. doi:10.1371/journal.pone.0002502

[42] Bioclimatic envelope modeling uses climate data within the current observed range of a species to bracket suitable climate conditions and then analyzes climate data over a broader region to assess the areas that are (a) suitable for the species currently and (b) will be suitable under future climate conditions. The difference between (a) and (b) is the potential impact of climate change on the species' ranges, which, unlike invasive and nuisance species, are likely to contract for native species. Bioclimatic requirements for a species to survive and reproduce may include, for instance, sustained maximum daily temperatures under a threshold or a minimum monthly level of rainfall.

4. **Estimate costs of re-introduction.** Two approaches to costing impacts could be considered: (1) estimate the impacts of the lost ecosystem services from reduction in native species coverage, which may include aesthetic and recreational values, flood peak dampening, water quality, and others; or (2) estimate the costs of maintaining native species coverage by active management and reestablishment. It is uncertain which of these approaches would generate higher values, but the second approach is considerably more straightforward. Current cost estimates from the DNREC Division of Fish and Wildlife include $300/acre for early successional establishment and about $200/acre for reforestation.[43] Note that DNREC staff suggest that these numbers could be twice as high depending on species composition.
5. **Apply re-introduction costs to incremental changes in the native range.** Next, the re-introduction costs per acre would be applied to the areas where the species was modeled as extirpated under the climate projections considered. A challenge will be determining how extensive an area to include in the analysis; at the high-end, much of the state could be included in the reestablishment effort, so the analysis will likely need to focus only on a subset of species and sensitive habitat areas within the state.

The data sources that would be needed for this analysis are listed in **Table 3-8**.

TABLE 3-8. NATIVE PLANT SPECIES ANALYSIS DATA SOURCES AND NEEDS

DATA	DESCRIPTION	POTENTIAL SOURCE AND/OR EXAMPLES
Species of concern	The set of species that are selected for the analysis	DNREC.
Species range	County-level data on native species range	The source for native species data is uncertain. An example for invasive species is: Clark, T. 2015. A subcontinental reconstruction of invasion patterns and processes for the past two centuries. M.S. Thesis, Purdue University.
Bioclimatic variables	Species-specific climatic variables that constrain the habitat range of the native species	Examples for two invasive species are provided in Chapter 3.4.
Climatic variables	A gridded climate dataset that provides daily temperature and precipitation under baseline and future climate scenarios, which are needed to model bioclimatic requirements	Pierce, D. W., Cayan, D.R. and Thrasher, B.L. 2014. Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, 15, 2558-2585.
Areas to focus analysis	The analysis will likely only include a subset of native habitat that is particularly important	DNREC.
Cost to reestablish species	The cost per acre to reestablish native species, including early successional establishment and reforestation	DNREC, Division of Fish and Wildlife.

Although insufficient information was available to conduct this analysis, the above steps and data needs provide one approach to estimating the economic impacts of climate change on native plant species.

---

[43] Via personal communications with the DNREC Division of Fish and Wildlife.

3.4 THE SPREAD OF INVASIVE PLANT SPECIES

The spread of invasive plant species on forest, beach and dune, and wetland and aquatic ecosystems

The disruptive and detrimental effects of invasive plant species on native ecosystems are well documented, and numerous invasive plant species are currently present in Delaware. Although few comprehensive studies of the economic impacts of invasive species have been conducted, Pimentel et al. (2005) report total environmental and economic costs to the U.S. at $120 billion per year.[44] Other research has shown that invasive species distributions are affected by climate, and that projected warming conditions under climate change are likely to improve the suitability of more areas for invasive species currently confined to warmer, more southernly regions (e.g., research by Dukes et al., 2009).[45] However, few studies have monetized how climate change affects the impacts of invasive species.

We estimate these effects for Delaware by first analyzing the expansion of potential habitat for two southeastern U.S. invasive species found in states surrounding Delaware and then applying this expansion to Delaware's ongoing management costs.[46] This approach uses these two species as a proxy for future invasive species expansion in Delaware more generally. Given the absence of Delaware-specific species coverage information and invasive species management costs, it is best to view the costs presented in this analysis as illustrative. The limitations below provide more context on how the analysis can be enhanced in the future.

Methods:

This approach relies on species bioclimate envelope modeling, using climate data within the current observed range of a species to bracket suitable climate conditions, and then analyzing climate data over a broader region to assess the areas that are (a) suitable for the species currently, and (b) will be suitable under future climate conditions. The difference between (a) and (b) is the potential impact of climate change on the species' ranges. The approach involves several steps:

1. **Select plant species for analysis**. The criteria for inclusion of a species are its sensitivity to climate change, non-prevalence across Delaware in the baseline period, and data available on the existing range and bioclimatic requirements. The DNREC Divisions of Parks and Recreation and Fish and Wildlife noted several key species of concern; however, none of these met the third criteria of having range and bioclimatic requirements available.[47] We instead relied on two southeastern species that are sensitive to climate change and have range and bioclimatic information readily available: Chinese

---

[44] Pimentel, D., R. Zuniga, D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics. 52:273-288.

[45] Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., … and J. Ehrenfeld. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? One of a selection of papers from NE Forests 2100: A Synthesis of Climate Change Impacts on Forests of the Northeastern US and Eastern Canada. Canadian Journal of Forest Research 39(2):231-248.

[46] Note that both the costs of native species reestablishment and invasive species control are adaptation costs we use to proxy for the impact costs, which would be much more difficult to quantify. The impacts of invasive species are partly captured in the control of current and predicted invasive and nuisance species category under Agriculture below.

[47] The following invasive species of concern by the DNREC Divisions of Parks and Recreation and Fish and Wildlife: autumn olive (*Elaeagnus umbellata*), Canada thistle (*Cirsium arvense*), dog fennel (*Eupatorium capillifolium*), lespedeza (*Lespedeza* varieties), mile-a-minute (*Persicaria perfoliata*), and phragmites (common reed, *Phragmites australis*).

tallow (*Triadica sebifera*) and cogongrass *(Imperata cylindrica*). Chinese tallow is a tree native to eastern China originally introduced to the U.S. in the 1700s and has become naturalized through the southeastern U.S. from North Carolina to eastern Texas and in California. Cogongrass is an aggressive exotic perennial grass that is on the Federal list of noxious weeks, and has been established in the southeastern U.S.

FIGURE 3-2. CHINESE TALLOW LEAVES (T. sebifera) (LEFT) [48] AND COGONGRASS (I. cylindrica) (RIGHT) [49]

2. **Develop bioclimatic envelopes that describe suitable habitat conditions for each species.** County-level data on species invaded ranges are available from Clark (2015).[50] We overlaid these ranges onto a 1/16 x 1/16 degree baseline climate dataset applied by Pierce et al. (2014)[51], and then developed two sets of temperature and precipitation conditions from the baseline climate data that characterize the species' invaded ranges. To do this, we used previously identified, species-specific climatic variables that constrain Chinese tallow (*T. sebifera*) and cogongrass (*I. cylindrica*) distribution in the southeastern U.S. (Bradley et al. 2010, Sui et al 2014), and assigned each variable a value using the baseline climate data within the species' invaded ranges.[52] See **Table 3-9** for the list of variables used to determine each envelope.

---

[48] Image source https://www.aces.edu/blog/topics/forestry-wildlife/management-options-for-chinese-tallowtree/

[49] Image source https://hgic.clemson.edu/factsheet/cogongrass/

[50] Clark, T. 2015. A subcontinental reconstruction of invasion patterns and processes for the past two centuries. M.S. Thesis, Purdue University.

[51] Pierce, D. W., D. R. Cayan, and B. L. Thrasher, 2014: Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, volume 15, page 2558-2585.

[52] Bradley, B.A., Wilcove, D.S., and M. Oppenheimer. 2010. Climate change increases risk of plant invasion in the Eastern United States. Biological Invasions 12:1855-1872; Sui, Z., Fan, Z., and X. Fan. 2014. Predicting Triadica sebifera occupied probability by climate envelope models in the southeastern United States. Proceedings of the 9th Southern Forestry and Natural Resource Management GIS Conference, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia USA. Merry, K., Bettinger, P., Brown, T., Cieszewski, C., Hung, I-K., and Q. Meng, Eds. 2014. pp 77-87.

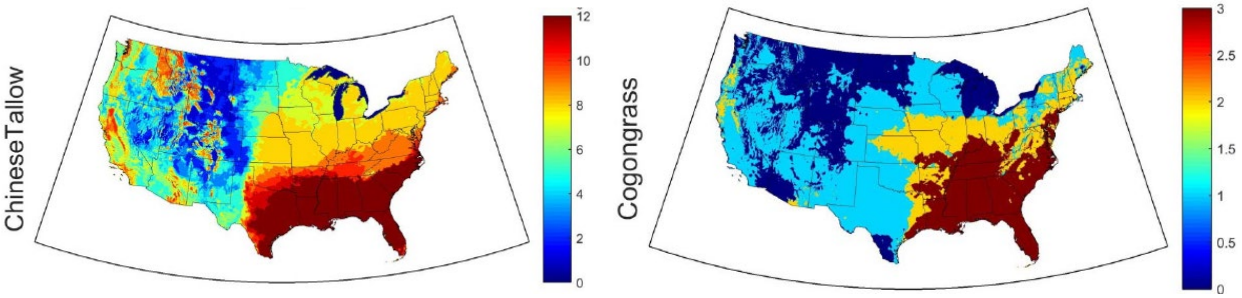
TABLE 3-9. CLIMATIC VARIABLES USED TO CREATE SPECIES BIOCLIMATE ENVELOPES

CHINESE TALLOW (*T. sebifera*)[53]	COGONGRASS (*I. cylindrica*)[54]
Annual Mean Temperature	September Maximum Temperature
Mean Diurnal Range (Mean of monthly (Max Temp - Min Temp)	July Precipitation
Isothermality (Mean Diurnal Range/Temperature Annual Range)*(100)	Average Precipitation
Temperature Seasonality (Standard Deviation *100)	-
Mean Temperature of Driest Quarter	-
Mean Temperature of Coldest Quarter	-
Annual Precipitation	-
Precipitation of Wettest Month	-
Precipitation of Wettest Quarter	-
Precipitation of Driest Quarter	-
Precipitation of Warmest Quarter	-
Precipitation of Coldest Quarter	-

3. **Determine potentially suitable habitat range using baseline and future climate conditions.** We next analyzed where the above bioclimatic conditions were met for each species using historical climate data. **Figure 3-3** shows a count of the number of conditions that are met for each species across the contiguous U.S. The areas in dark red meet all bioclimatic conditions for each species, but are not necessarily occupied — the current invaded range is considerably smaller than the full potential invaded range due to non-climatic constraints. Next, for each GCM-RCP combination, we applied the same process under future climate conditions by era. This produced 12 future invaded range outcomes: 6 GCMs x 2 RCPs.

FIGURE 3-3. POTENTIAL SPECIES DISTRIBUTION BASED ON BASELINE CLIMATE CONDITIONS (1986 TO 2005)

Results based on IEc analysis. Shading of the figure reflects the number of bioclimatic requirements met in each region. Chinese tallow has a total of 12 requirements, whereas Cogongrass has three. The deep red region is the envelope that meets all requirements (i.e., the current envelope), whereas dark blue meets none of the requirements.



---

[53] Variables identified by Sui, Z., Fan, Z., and X. Fan. 2014. Predicting Triadica sebifera occupied probability by climate envelope models in the southeastern United States. Proceedings of the 9th Southern Forestry and Natural Resource Management GIS Conference, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia USA. Merry, K., Bettinger, P., Brown, T., Cieszewski, C., Hung, I-K., and Q. Meng, Eds. 2014. pp 77-87.

[54] Variables identified by Bradley, B.A., Wilcove, D.S., and M. Oppenheimer. 2010. Climate change increases risk of plant invasion in the Eastern United States. Biological Invasions 12:1855-1872.

4. **Calculate the difference in area between the baseline and future suitable habitat.** The aim of this step was to understand the potential increase in the area of each invasive species under climate change. To capture the effect of climate change, we develop a set of multipliers for each GCM-RCP scenario and future period: the area of potentially suitable habitat range under each scenario and period divided by suitable habitat under the baseline. Estimating this change in area is best done on a broad regional scale given uncertainties in how species will migrate into specific regions (such as Delaware), so the area we consider includes Delaware and the seven surrounding states: New York, New Jersey, Pennsylvania, Maryland, West Virginia, Virginia, and North Carolina. The resulting area multipliers for cogongrass and Chinese tallow are used as a proxy for the spread of a much broader set of invasive species across Delaware.
5. **Estimate management costs currently spent in Delaware.** The analysis applies these multipliers to available current management costs in Delaware. Current costs would ideally include all government and landowner expenditures on invasives control and management, including monetized volunteer time with DNREC, the Invasive Species Council, or other organizations.[55] However, costs were only available from two divisions within DNREC: (1) the Division of Fish and Wildlife documents $300,000 per year for a phragmites control cost share program, which would treat about 6,000 acres; and (2) the Division of Parks and Recreation forecasts $132,000 in FY2021 expenses for the Environmental Stewardship program. We assume these costs ($432,000) are spread across the three counties according to area. Both divisions acknowledged that these were incomplete cost estimates. For example, other invasive species have different management costs and individual parks are likely to spend additional resources on invasives control.[56]
6. **Apply management costs to annual incremental change in invaded species ranges**. We then apply the suitable habitat multipliers for Chinese tallow and cogongrass to the available current management costs, to provide an illustrative estimate of increased costs under climate change.

The data sources used in this analysis are listed in **Table 3-10**.

---

[55] Delaware State Parks hosted 38 invasive removal events in 2020 (see calendar: https://www.destateparks.com/Volunteer/Calendars), and volunteer time has been monetized in other contexts (e.g., see City of Raleigh. 2020. Invasives Species Program Phase 1 Report. Accessed from https://cityofraleigh0drupal.blob.core.usgovcloudapi.net/drupal-prod/COR24/invasive-report-web.pdf). To illustrate the potential importance of these events, Youth Conservation Corps events included 24 members and 4 team leaders, who spent 4,704 hours with a cost of $38,000.

[56] Note that per acre costs can also be considerably higher than the phragmites control program, which is $50/acre for herbicide application by helicopter. In a study for the Department of Interior, IEc found that Chinese tallow treatments are approximately $25,000/acre for a seven-year program [CTTF (Chinese Tallow Task Force). 2005. Chinese Tallow Management Plan for Florida, 1st ed. C.M. McCormick, Chair. Florida Exotic Pest Plant Council. 83 pp.], and Cogongrass treatments are roughly $5,000/acre for a four-year program [McClure, M., and J. Johnson. 2010. Cogongrass eradication strategies. Georgia Forest Commission. 3 pp., Alabama Forestry Commission. 2012. Final Report of the American Reinvestment and Recovery Act, Award Number 09-DG-11084419-041 – ARRA, Cogongrass Program (Alabama Cogongrass Control Center). Submitted by Larson & McGowin, Inc. 77pp.].

TABLE 3-10. INVASIVE PLANT SPECIES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Climatic variables	The LOCA dataset provides daily temperature and precipitation under baseline and future climate scenarios, which we use to examine bioclimatic requirements	Pierce, D. W., Cayan, D.R. and Thrasher, B.L. 2014. Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, 15, 2558-2585.
Species range	County-level data on invaded species range	Clark, T. 2015. A subcontinental reconstruction of invasion patterns and processes for the past two centuries. M.S. Thesis, Purdue University.
Bioclimatic variables	Species-specific climatic variables that constrain Chinese tallow and cogongrass distribution in the southeastern U.S.	Bradley, B.A., Wilcove, D.S., and Oppenheimer, M. 2010. Climate change increases risk of plant invasion in the Eastern United States. Biological Invasions, 12, 1855-1872. Sui, Z., Fan, Z., and Fan, X. 2014. Predicting Triadica sebifera occupied probability by climate envelope models in the southeastern United States. Proceedings of the 9th Southern Forestry and Natural Resource Management GIS Conference, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia USA. Merry, K., Bettinger, P., Brown, T., Cieszewski, C., Hung, I-K., and Q. Meng, Eds. 77-87.
Invasive species management costs	Costs of a phragmites management program and an invasive species management program	DNREC, Division of Fish and Wildlife and Division of Parks and Recreation.

Results:

The results of bioclimatic modeling demonstrate the potential for increases in the species ranges for both Chinese tallow and cogongrass. The light gray portions of **Figure 3-4** represent the current potential range of the species (i.e., its current climate envelope), and the orange to red areas represents a count of the six GCMs showing the potential future range of the species under the emissions scenarios for mid-century (2050) and late century (2090).

Table 3-11 shows the share of the eight-state region analyzed (NY, NJ, PA, MD, DE, WV, VA, and NC) that is currently suitable for each species, and suitable under future climate change scenarios, with percentage increases under climate change listed in lower half of the table. Chinese tallow is currently suitable in only 14 percent of the eight-state region, but rises to as much as 25 percent by late century. This increase from 14 to 25 percent coverage represents an 83 percent increase in the range. Cogongrass starts with a much higher share of suitability (58 percent), and by the end of the century conditions are suitable across nearly the entire region (95 percent), which represents a 65 percent increase in the range.

FIGURE 3-4. POTENTIAL RANGE OF CHINESE TALLOW AND COGONGRASS UNDER CURRENT CONDITIONS (LIGHT GRAY) AND FUTURE CONDITIONS (YELLOW TO RED)

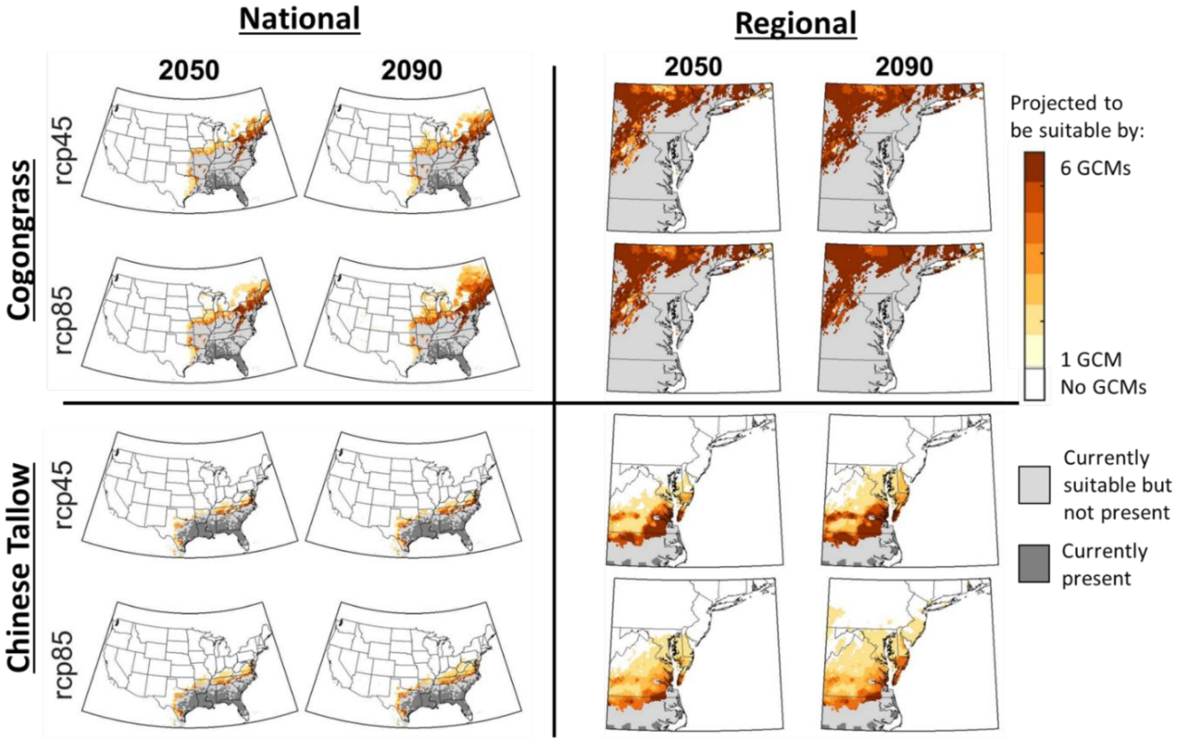


TABLE 3-11. CHANGE IN PROJECTED INVASIVE SPECIES COVERAGE OF THE EIGHT-STATE REGION SURROUNDNG DELAWARE FROM BASELINE UNDER CLIMATE CHANGE

The first metric shows the percentage of the eight-state region that is suitable for each species under the 1986 to 2005 baseline, and each future period, all rounded to whole percentages. The second metric then uses this information to calculate the percent change in the suitable area from the baseline to each future period. For example, Chinese tallow is suitable in 14 percent of the eight-state region under the baseline, and increases to 18 percent by the near century under RCP8.5. This change is a 29 percent increase i.e., 18/14 – 1 = 0.29.

METRIC	SPECIES	BASE-LINE	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
			RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Share of Eight-State Region Area with Suitable Conditions	Cogongrass	58%	80%	80%	90%	88%	95%	92%
	C. Tallow	14%	18%	18%	21%	22%	25%	24%
Percent Change in Area of Suitable Conditions, Relative to the Baseline	Cogongrass	-	40%	39%	56%	53%	65%	60%
	C. Tallow	-	29%	29%	53%	58%	83%	76%
	Average	-	**34%**	**34%**	**55%**	**55%**	**74%**	**68%**

Lastly, **Table 3-12** summarizes the increased management costs, which apply the average percentage increases in suitable area (last row of **Table 3-11** above) to the $432,000 currently spent on annual statewide management costs between the phragmites control and environmental stewardship programs. The future scenario results represent the additional species' management costs for the near, mid- and late century under each RCP and averaged across the six GCMs. The additional cost of implementing species control measures may range from $150,000 to $320,000 based on this stylized illustration of species expansion and available set of management costs.

TABLE 3-12. ANNUAL ECONOMIC IMPACTS FROM CLIMATE CHANGE ON INVASIVE SPECIES MANAGEMENT

Impacts are defined as an increase in invasive management expenditures relative to the baseline climate scenario (1986-2005) and 2019 phragmites control and environmental stewardship budget, measured in dollars (2019), per year and averaged over 6 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$53,000	$53,000	$85,000	$86,000	$110,000	$100,000
New Castle County	$33,000	$33,000	$52,000	$53,000	$71,000	$65,000
Sussex County	$62,000	$62,000	$99,000	$100,000	$130,000	$120,000
Delaware Total	**$150,000**	**$150,000**	**$240,000**	**$240,000**	**$320,000**	**$290,000**

Limitations:

- Due to the lack of available information on either the extent or the bioclimatic requirements for the key invasive species in Delaware, the analysis uses cogongrass and Chinese tallow as indicators of how those key species may promulgate under climate change. How these key species would spread would require further geospatial data, research on requirements, and analysis.
- More detailed current species occurrence information that includes species density (instead of just presence/absence) may be used to create more detailed bioclimate envelopes. Additional bioclimatic modeling may inform the development of other constraining parameters affecting species range expansion. Note that envelope modeling can provide rough estimates of the potential impact of climate change on species distributions, but caution must be paid in interpreting the results, as there are a variety of modeling-related limitations.[57]
- The analysis estimates the potential costs of future invasive species management programs rather than the economic impacts of invasive species in Delaware. Impacts may include effects on agricultural yields, aesthetic and recreational losses, impacts to the built environment (e.g., water supply), and losses in other ecosystem services that native species provide.
- Projected costs are based on the management expenses for a limited set of Delaware programs and would scale up if a broader set of costs were included. The analysis also assumes that management costs would scale up linearly with increases in the size of the bioclimatic envelopes, which may overestimate or underestimate the actual outcomes. It is unknown whether (a) actual invasive plant areas scale with bioclimatic envelope area and (b) costs scale linearly with spatial coverage.

---

[57] See Pearson, R.G. and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography 12:361-371.

3.5 LOSS OF FOREST, BEACH AND DUNE, AND WETLAND AND AQUATIC ECOSYSTEMS

Loss of forest, beach and dune, and wetland and aquatic ecosystems in relation to the ecosystem services they provide for water quality, flooding and storm surge, and habitat for commercially valuable species

Ecosystems in Delaware will be threatened by changing climatic and hydrological conditions, as well as by SLR and storm surge. We measure the change in ecosystem service provisions from wetlands due to SLR. Ecosystem services are valued based on natural goods provision, flood protection, and other natural services.

Methods:

We use data from the National Oceanic and Atmospheric Administration's (NOAA) Marsh Migration Model, which models wetland coverage for five types of wetlands (salt marsh, brackish/transitional, and three freshwater wetland types [forested, scrub or shrub, and emergent]) at varying SLR heights. In the model, land types convert over time as sea levels elevate, while developed area is held constant. This results in a "squeezing out" of coastal wetlands as sea level rises and reaches developed areas. The model provides results for three accretion rate assumptions, which parameterize the amount of vertical rise in the marsh's surface due to buildup of organic and inorganic material: high (6 mm per year), medium (4 mm per year), and low (2 mm per year) rates of accretion. Accretion can slow saltwater wetland loss if the accretion rate keeps pace with SLR; otherwise, saltwater wetlands are lost as they transition to open water.

IEc processed these results by county for the two NOAA SLR scenarios most closely aligned with the SLR trajectory for this analysis and for a "no SLR" baseline. We estimate impacts in each NOAA scenario for the central years of the future eras in this analysis (i.e., 0.75 ft, 1 ft, 3 ft) and average the two scenarios to estimate impacts in the central year of each era. We then linearly interpolate between the central year estimates to create an annual time series of impacts and compute averages over the 20-year eras (for more discussion of this process, see Chapter 2.2). The resulting data provides acres by wetland type and time period (i.e., baseline period and three future eras) from which we calculate the change in wetland area by type, relative to the no SLR baseline (i.e., year 2000).

Wetland area is valued in terms of flood protection services, natural goods provision (e.g., raw materials, food sources), and other natural services values (e.g., water quality provision, sediment removal). Sun and Carson (2020) estimate the flood protective effects of coastal wetlands as the expected avoided economic damage based on a historical dataset of hurricane flood damages across the U.S. Atlantic and Gulf Coasts at the county level.[58] We use flood protection values by county following Sun and Carson's values (Kent: $73/acre/yr; New Castle: $302/acre/yr; and Sussex: $392/acre/yr).[59] Constanza (2007), selected due to the proximity of the study site to Delaware and the dimensions of available data, provides values of natural goods provision and other natural services values (including flood protection) for wetland areas in New Jersey, differentiated by wetland type (i.e., freshwater-forested, freshwater-unforested, and

---

[58] Sun, F., & Carson, R. T. (2020). Coastal wetlands reduce property damage during tropical cyclones. *Proceedings of the National Academy of Sciences*, *117*(11), 5719-5725.

[59] The study considers saltwater and freshwater wetlands separately but does not find a significant difference in service value therefore we do not differentiate in our analysis.

saltwater).[60] We substitute the spatially refined flood protection values from Sun and Carson for the flood protection values from Constanza. The resulting schedule of ecosystem service values, per acre per year, are shown in **Table 3-13**.

TABLE 3-13. ECOSYSTEM SERVICES VALUES ($/ACRE/YEAR)

Values represent natural goods and environmental service provisions provided by wetlands, including flood protection services. Flood protection service values by county provided by Sun and Carson (2020), with natural goods and all other environmental services from Costanza (2007).

	FRESHWATER WETLANDS		SALTWATER WETLANDS
	FORESTED	NON-FORESTED	
	(FORESTED)	(SHRUB & EMERGENT)	(SALT MARSH & BRACKISH/TRANSITIONAL)
Kent County	$11,110	$11,051	$8,140
New Castle County	$11,339	$11,279	$8,368
Sussex County	$11,429	$11,370	$8,459

The data sources used in this analysis are summarized in **Table 3-14**.

TABLE 3-14. ECOSYSTEM SERVICES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
NOAA Marsh Migration Model	Land coverage by wetland type and sea elevation	NOAA. 2017. Detailed Method for Mapping Sea Level Rise Marsh Migration. https://coast.noaa.gov
Ecosystem services values	Wetlands flood protection value	Sun, F. and Carson, R. T. 2020. Coastal wetlands reduce property damage during tropical cyclones. Proceedings of the National Academy of Sciences, 117(11), 5719-5725.
	Wetlands natural goods and services	Costanza, R. 2007. Valuing New Jersey's Natural Capital: An Assessment of the Economic Value of the State's Natural Resources.

Results:

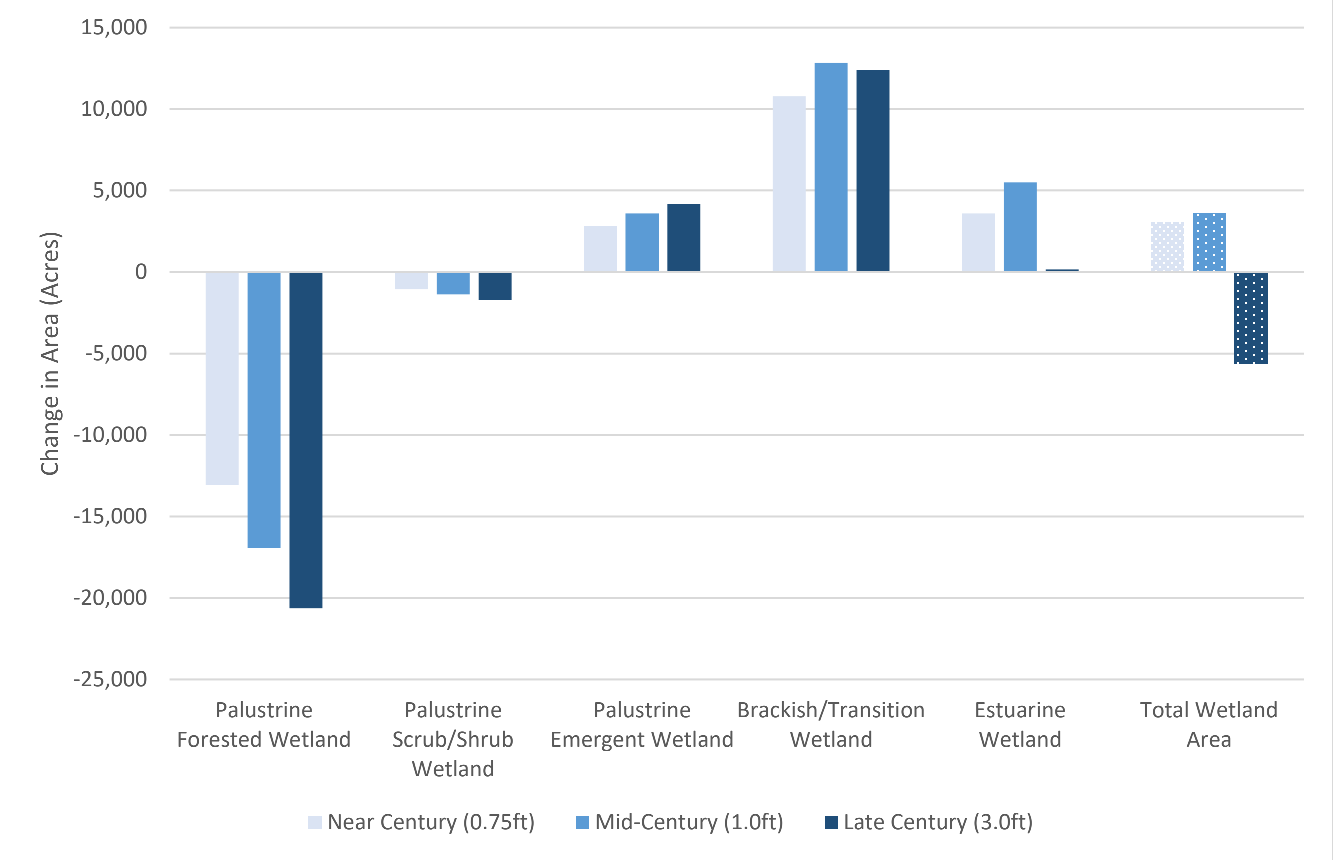
As shown in **Figure 3-5**, total wetland area is projected to increase through mid-century, as SLR causes the conversion of non-developed upland areas to wetlands, particularly brackish/transition wetlands. Baseline wetland areas, as reported in the NOAA March Migration Model, either remain intact in the future, convert to other land cover types (including other types of wetlands), or convert to open water. Freshwater forested wetland area declines over the century, and by late century, total wetland areas decrease below modeled baseline levels (i.e., no SLR, year 2000) for a net loss in area. Both Kent and Sussex Counties are projected to lose about five percent of their total wetland area by late century, while New Castle County is projected to have a two percent loss.

---

[60] Costanza, R. (2007). Valuing New Jersey's Natural Capital: An Assessment of the Economic Value of the State's Natural Resources.

FIGURE 3-5. CHANGE IN WETLAND AREA BY TYPE OF WETLAND FOR 4MM ACCRETION SCENARIO

Change in wetland area (acres), relative to the year 2000 baseline. The 4mm/yr. accretion scenario is presented as the central case. Total wetland area represents the sum of all wetland types.



As shown in **Table 3-15**, even as the total area increases during the near and mid-century, the total value decreases, as higher value forested wetlands (average of $11,293/acre/year) are converted to lower value brackish wetlands ($8,322/acre/year) or unconsolidated shore/open water, which are not valued in this study. Kent and Sussex Counties experience an increase in total wetland area through mid-century while New Castle County experiences a decrease in total area throughout the century. In Kent County, the net increase in wetland area results in a net increase in ecosystem value early in the century. In Sussex County, the net increase in wetland areas is driven primarily by lower-value saltwater marshes, including some conversion from higher-value freshwater marshes, resulting in a net loss in value. The total undiscounted annual lost value ranges from $110 million (6mm/yr) to $230 million (2mm/yr) by the late century.

The values shown in **Table 3-15** represent the average annual loss in wetland area for each county and under each accretion assumption. Because the ecosystem service values used in this analysis represent the value of one year of services, impacts in future eras represent the value of the total change in area relative to the baseline. In other words, if an acre is lost near century, the value of that acre is reported for that era and all subsequent eras, as that flow of services continues to be absent.

TABLE 3-15. ANNUAL ECONOMIC IMPACTS TO ECOSYSTEM SERVICES VALUES FROM SEA LEVEL RISE ($MILLION)

Economic impacts defined as lost ecosystem service value compared to ecosystem service provision in a no SLR baseline (year 2000). Measured in millions of dollars (2019) per year. Values may not sum due to rounding.

		Near Century (2020-2039)	Mid-Century (2040-2059)	Late Century (2080-2099)
2mm/yr. sediment accretion	Kent County	$12	$17	$51
	New Castle County	$21	$27	$52
	Sussex County	$36	$50	$130
	Delaware Total	**$68**	**$94**	**$230**
4mm/yr. sediment accretion	Kent County	$9.6	$29	$29
	New Castle County	$16	$39	$39
	Sussex County	$29	$91	$91
	Delaware Total	**$55**	**$160**	**$160**
6mm/yr. sediment accretion	Kent County	$5.2	$19	$19
	New Castle County	$8.1	$30	$30
	Sussex County	$17	$61	$61
	Delaware Total	**$30**	**$110**	**$110**

Limitations:

- This analysis does not consider the impacts of other climatic changes, such as changing habitat suitability requirements, increased wildfire risk, etc.
- We do not consider the impact of storm surge, which may cause some damage to ecosystems but does not result in permanent inundation/loss. However, as storm intensity and frequency increases, the long-term impacts of wetland damage may become a more significant issue.
- As wetland area grows, it is replacing a current land use that likely has a non-zero value. This analysis does not consider the opportunity cost of this conversion. Furthermore, we also do not include any value for open water, which has a non-zero value.
- The Costanza (2007) wetland values are generated by first calculating the total value of services provided by a wetland and then dividing that total by the number of acres to estimate a value per acre. The per-acre values do not necessarily represent the marginal value of wetlands. In other words, it is not clear that the value of losing the entire wetland divided by number of acres is equal to the value of losing one acre of wetland. The modeled acres lost in this analysis could be more or less valuable than the average value calculated in Costanza (2007). Additionally, the total value of services are transferred from a study carried out for New Jersey; the use of Delaware specific-results would improve the analysis.

- This analysis does not consider non-wetland habitats that hold high value in the region, particularly beaches. Beach nourishment is required to maintain beach area for recreational purposes, a need that is expected to increase under climate change due to SLR and more frequent and intense storm activity. Available data suggests that over the 20 year period from 1996 to 2015, costs to nourish Delaware beaches totaled approximately $220 million to place approximately 22 million cubic yards of sand.[61] Increases in beach nourishment costs as sea-level rises are likely, but are difficult to estimate without additional data on total areas to be nourished, the length of replenishment cycles, and the availability of sand for renourishment from borrow sites. Under the current funding structure, the state funds nourishment activities through tourism revenues. If current revenues are not sufficient to cover the increased demand for nourishment in the future, it could trigger a cyclical effect where underfunded nourishment projects lead to under maintained beaches and decreased tourism revenue, further constraining available funds for nourishment activities. These impacts are not included in this analysis.

---

[61] Data from: https://www.delaware-surf-fishing.com/what-does-beach-replenishment-really-cost/ .

3.6 WATER QUALITY DUE TO SEA LEVEL RISE IMPACTS

Water quality due to SLR impacts on public/privately-owned municipal wastewater treatment facilities and home septic systems

Coastal infrastructure, including municipal wastewater treatment facilities and home septic systems are at risk due to permanent inundation of saltwater from SLR and occasional, but increasingly severe, flooding from storm surges.

Methods:

The wastewater systems at risk were identified by overlaying the two asset layers (permitted septic systems and wastewater treatment plants) with SLR inundation maps from the Delaware Coastal Inundation model plus estimated storm surge heights for the three Delaware counties (Chapter 2.2 offers a more detailed description of the SLR overlay process). The asset datasets included 31 wastewater treatment plants and nearly 100,000 septic systems. We eliminated septic systems that are no longer in use, leaving 11,371 current systems.[62]

Costing damages from SLR and storm surge on wastewater treatment plants and septic systems is challenging due to the unique characteristics of each facility, the potential releases, and the variability of damage related to flood depth — information that is not available in the current SLR projection datasets. Even more difficult is estimating the natural resource damage caused by unmitigated floods and releases; therefore, we used treatment facility reconstruction and repair costs as proxies for the value of the environmental damage. We assumed that the at-risk facilities would be rebuilt elsewhere prior to SLR inundation, at a cost of $15 million per wastewater treatment plant and $6,000 per septic system.[63] For storm surge impacts, we assume that no protective measures or advance relocation takes place and instead characterized impacts using repair costs accrued after a flooding event ($4 million per wastewater treatment plant and $650 to pump out septic systems for each flooding event that the asset is inundated). These costs are intended to represent an average level of damage but may be higher or lower at a particular facility for a particular event.[64] We assume relocation costs were a one-time expenditure (i.e., costs to relocate a facility in the near century are not also included in the late century) but storm surge flooding impacts could occur more than once (i.e., the same facility could incur storm surge damage in both the near and mid-century).

The data sources used in this analysis are summarized in **Table 3-16**.

---

[62] Note that it is possible that septic systems no longer in use could still pose a threat if the system is not closed out properly or removed. Absent further detailed data on the condition of systems no longer in use, we limited the analysis to only active systems. However, this likely creates an underestimation of potential impacts.

[63] The $15 million estimate for wastewater treatment plant rebuilding was loosely based on a preliminary engineering report for a new treatment plant for the Delaware County Regional Wastewater District, estimating costs of $10.1 million (http://dcrwd.com/wp-content/uploads/2019/07/July-5-2019-Proposed-Wastewater-Treatment-Facility-Executive-Summary.pdf). As the SLR inundation scenario would also include some remediation or deconstruction, we assumed $15 million for the total project.

[64] As a limited number of wastewater treatment plants are vulnerable to SLR and storm surge, it may be possible to assign site-specific replacement and repair costs.

TABLE 3-16. WASTEWATER TREATMENT PLANTS AND SEPTIC SYSTEMS ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Permitted septic systems	Coordinates for 96,354 septic systems, including 11,371 current systems[65]	DNREC.
Wastewater treatment plants	GIS points for 31 wastewater treatment plants	DNREC.
Cost data	National average septic system removal and replacement	Online search (https://homeguide.com/costs/septic-tank-system-cost).
	Regional average septic system pumping	Online search (https://kompareit.com/homeandgarden/plumbing-compare-septic-tank-cleaning-cost.html).
	Wastewater treatment plant reconstruction	Preliminary engineering report for Delaware County Regional Wastewater District. http://dcrwd.com/wp-content/uploads/2019/07/July-5-2019-Proposed-Wastewater-Treatment-Facility-Executive-Summary.pdf
	Wastewater treatment plant flood damage repair	Based on flooding events and repair data for historical floods in Nashville, TN. https://www.michigan.gov/documents/deq/deq-rmd-wws-wwss12-pres1_390429_7.pdf

Results:

As shown in **Table 3-17**, economic impacts are projected to be relatively moderate for SLR-based relocations. The vast majority of wastewater treatment plants are located outside of the projected SLR flood zone of up to three feet. Only one site (Port Penn) is projected to see permanent inundation from SLR but only at three feet of SLR in the late century. 740 septic systems are expected to be inundated at three feet of SLR, 649 of which are in Sussex County. However, this is a small proportion of in-use septic systems (1.2 percent), and relative to the cost of relocating wastewater treatment plants, septic system costs are minimal.

TABLE 3-17. ANNUAL ECONOMIC IMPACTS TO WASTEWATER TREATMENT PLANTS AND SEPTIC SYSTEMS FROM SEA LEVEL RISE

Impacts are defined as facility reconstruction costs above the no-SLR baseline (year 2000), measured in dollars (2019). Values may not sum due to rounding.

	Near Century (2020-2039)	Mid-Century (2040-2059)	Late Century (2080-2099)
Kent County	$2,200	$3,700	$4,400
New Castle County	$170,000	$290,000	$190,000
Sussex County	$22,000	$210,000	$420,000
Delaware Total	**$200,000**	**$500,000**	**$620,000**

As shown in **Table 3-18**, storm surge damages have the potential to be costly: three additional wastewater treatment plants are at risk of storm surge flooding under certain surge scenarios (i.e.,

---

[65] We identified current systems as those with a permit status of "Approved", "Pending", "System Inspection", "Application Received", "Active", "Completion Report Received", or "Call Notification Received".

the Delaware City, Seaford, and Lewes wastewater treatment plants). Note that storm surge impacts are predicted to decrease over time as SLR forces relocation of facilities that would be vulnerable to storm surge earlier in the century (i.e., early in the century a facility might be vulnerable to storm surge damage, but by late century, that facility faces permanent SLR inundation and therefore has relocated).

TABLE 3-18. ECONOMIC IMPACTS OF STORM SURGE EVENTS TO WASTEWATER TREATMENT FACILITIES ($MILLION)

Economic impacts are defined as repairs resulting from 1-percent and 10-percent storm surge events, measured in millions of dollars (2019). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions. above projected SLR in each era. The values below represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year). Values may not sum due to rounding.

	Near Century (2020-2039)		Mid-Century (2040-2059)		Late Century (2080-2099)	
Storm Event	10% storm	1% storm	10% storm	1% storm	10% storm	1% storm
Kent County	$0.015	$0.020	$0.020	$0.025	$0.018	$0.025
New Castle County	$5.0	$7.0	$7.0	$6.2	$5.8	$4.0
Sussex County	$3.9	$7.7	$7.7	$8.2	$4.6	$4.4
Delaware Total	**$8.9**	**$15**	**$15**	**$14**	**$10**	**$8.4**

Limitations:

- Septic tanks may experience damage before the location experiences surface inundation due to rising groundwater tables from SLR. Conversely, some septic tanks may be elevated or have other technology that make them less vulnerable to flooding. While the use of SLR inundation maps approximates the affected areas, such potential risk mitigating or risk increasing site-specific conditions are not considered.
- The available inundation maps do not provide flood depths and therefore we do not have specific information for which a depth-damage function could be used to differentiate impacts, particularly at wastewater treatment plants. We assume average damages for any object falling within the inundated area, regardless of flood height.
- We use an average repair and rebuild cost for wastewater treatment plants; however, these costs will vary by site based on a number of conditions, including the size of the plant and the size of the population served.
- This analysis considered currently identified wastewater treatment plants and septic systems and does not account for potential growth and land development over time. The results also do not reflect unpermitted septic systems which exist in the state or inactive systems that may still pose as a risk for contamination.
- While we exclude any assets that appear to already currently be inundated at mean higher high water levels, we do not exclude sites that appear to currently be affected by storm surge.

3.7 CONTAMINATED SOILS AND WATER QUALITY

The impact of contaminated soils on water quality if current and historic industrial and/or brownfield areas flood under predicted SLR scenarios

As sea levels rise, contaminated sites, and to some extent remediated sites are at risk of contaminant release from rising groundwater tables, flood events, and permanent inundation.[66] In this analysis we estimate the cost to remove contamination from sites at risk of being permanently inundated and the response costs at sites that are flooded during future storm events.

Methods:

We estimate damages for three categories of contaminated sites: leaking underground storage tanks, remediation sites of high concern (a subset of impacted sites identified by the DNREC Remediation Section that they considered of high concern should a release occur for the purpose of this analysis), and other remediation sites. Here, we employ a similar approach to the water quality analysis described in Chapter 3.6. We intersect contaminated sites regulated under Delaware Hazardous Substance Cleanup Act programs with projected areas of inundation from the Delaware SLR Inundation model. See Chapter 2.2 for a more detailed description of the SLR overlay process. This step results in the identification of the contaminated area inundated in each era due to SLR and at each storm surge event (i.e., 1-percent and 10-percent storms).

We assume that areas permanently inundated due to SLR will require soil removal to avoid harmful releases and that areas inundated during a storm surge events will require site cleanup. Soil removal and cleanup costs vary by site-specific characteristics; however, it is not feasible to collect these for individual sites given the scale of this statewide analysis. Soil removal costs are one-time expenditures (i.e., the contaminants are removed from the site upon initial inundation and do not require continued expense) while storm surge clean up can occur repeatedly (i.e., a site could flood multiple times due to storm surge, and each event would require cleanup activity). We use several known cost points for soil removal and site cleanup and scale for the likely magnitude of costs at each site in the analysis. DNREC provided average costs for leaking underground storage tank removal ($7,000 to $13,000 per tank) and cleanup costs ($120,000 to $183,343 per tank). DRPA Incorporated (2000) provide average unit costs for land treatment related to hazardous ($149/ton) and non-hazardous ($26/ton) waste, as well as soil/waste removal and backfill costs ($31/cubic yard).[67],[68] We match these costs to the three site types (i.e., leaking underground storage tanks, high concern sites with hazardous waste, other remediation sites with non-hazardous waste), as shown in **Table 3-19**.

---

[66] In this analysis, we define contaminated sites as those sites regulated under Delaware Hazardous Substance Cleanup Act.

[67] DRPA Incorporated. (2000). Unit cost compendium: data and algorithms for estimating costs associated with “cradle-to-grave” management of RCRA solid and hazardous wastes. Prepared for U.S. Environmental Protection Agency Office of Solid Waste. Available at https://ertpvu.org/RCRA/Documents/Financial%20Assurance/Unit%20Cost%20Compendium-EPA-HQ-RCRA-2002-0031-0429.pdf

[68] Values presented here are in 2019 dollars. Original values in the DRPA report are in year 2000 dollars; we adjust to 2019 dollars using the BLS CPI (factor of 1.48).

TABLE 3-19. SOIL REMOVAL AND CLEAN UP COSTS FOR CONTAMINATED SITES

SITE TYPE	STORM SURGE INUNDATION COST (RELEASE CLEAN UP)	SLR INUNDATION COST (SOIL REMOVAL)
Leaking underground storage tanks	**$151,672 per tank** *Average of range of leaking underground storage tank cleanup costs as provided by DNREC*	**$10,000 per tank** *Average of range of leaking underground storage tank removal cost as provided by DNREC*
Remediation sites of high concern	**$99,442 per acre** *Assumes 1,500 tons of contaminated soil per acre of contaminated site requires treatment following flooding, at a cost of $149 per ton (DRPA, 2000)*	**$30,609 per acre** *Assumes 1,000 cubic yards of contaminated soil per acre of contaminated site is removed (excavation and backfill) prior to permanent SLR inundation at a cost of $31 per ton (DRPA, 2000)*
Other remediation sites	**$17,390 per acre** *Assumes 1,500 tons of contaminated soil per acre of contaminated site requires treatment following flooding, at a cost of $26 per ton (DRPA, 2000)*	

The data sources used in this analysis are summarized in **Table 3-20**.

TABLE 3-20. CONTAMINATED SOILS ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Contaminated Sites	Polygon shapefile of remediation sites in Delaware	DNREC.
Leaking Underground Storage Tanks	Point shapefile of 2,771 leaking underground storage tanks in Delaware	DNREC.
Repair and Replacement Costs	Remove and replace leaking underground storage tank (cost per unit)	See Table 3-19.
	Remediate release from leaking underground storage tank (cost per unit)	
	Remove contaminated soil at remediation site (cost per cubic yard)	
	Remediate contaminated soil release at remediation site (cost per ton)	

Results:

As shown in **Table 3-21**, annual SLR damages for sites of concern are predicted to decrease over the course of the century, as sites are inundated and treated in the near- and mid- century and therefore are no longer at risk later in the century.

TABLE 3-21. ANNUAL ECONOMIC IMPACTS FROM CONTAMINATED SITES DUE TO SEA LEVEL RISE ($MILLION)

Impacts are defined as soil removal costs for the area inundated above the no-SLR baseline (year 2000), measured in millions of dollars (2019) per year. Values may not sum due to rounding.

	Near Century (2020-2039)	Mid-Century (2040-2059)	Late Century (2080-2099)
Kent County	$1.10	$0.73	$0.43
New Castle County	$0.19	$0.36	$0.47
Sussex County	$0.08	$0.07	$0.06
Delaware Total	**$1.4**	**$1.2**	**$1.0**

As shown in **Table 3-22**, the cleanup of leaking underground storage tanks after storm surge flooding is a large driver of the costs, equaling or surpassing costs for removing soil at other contaminated sites, particularly in the late century.

TABLE 3-22. ECONOMICS IMPACTS OF STORM SURGE ON CONTAMINATED SITES ($MILLION)

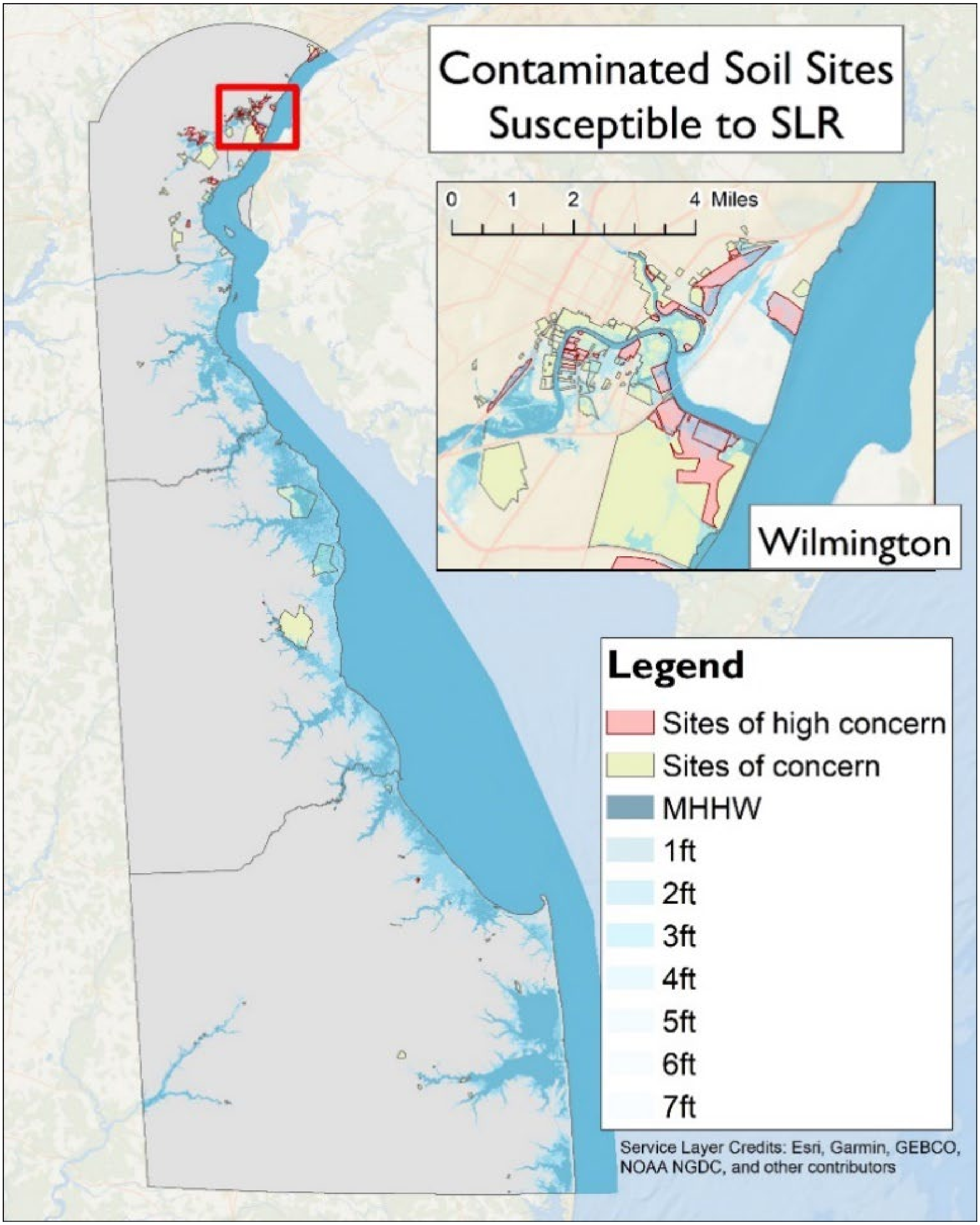
Economic impacts are defined as hazardous and non-hazardous waste cleanup costs for the area inundated under a 10-percent and 1-percent storm surge event, measured in millions of dollars (2019) per year. The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The values below represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year). Values may not sum due to rounding.

	Near Century (2020-2039)		Mid-Century (2040-2059)		Late Century (2080-2099)	
Storm Event	10% storm	1% storm	10% storm	1% storm	10% storm	1% storm
Kent County	$26	$33	$27	$30	$20	$22
New Castle County	$19	$24	$23	$29	$22	$29
Sussex County	$12	$10	$13	$12	$11	$11
Delaware Total	**$56**	**$68**	**$63**	**$71**	**$54**	**$61**

As shown in **Figure 3-6**, the majority of contaminated sites susceptible to SLR are found in New Castle County, particularly in the South Wilmington area where contaminated sites fall within the expected storm surge flood zone this century.

FIGURE 3-6. CONTAMINATED SOIL SITES SUSCEPTIBLE TO INUNDATION DUE TO SLR AND STORM SURGE

Map shows the contaminated soil sites susceptible to inundation at integer foot-increments of SLR (or SLR and storm surge). For example, the 3 ft layer in this map corresponds to the expected SLR in 2090.



Limitations:

- Site specific contaminant information, and therefore remediation and removal costs, are not available at a statewide level that lends itself to this type of analysis. The costs used in this analysis represent national average costs and likely overestimate costs at certain sites and underestimate costs at other sites.
- We allow for sites to incur storm surge damages in each era. While subsequent floods may be less costly if initial cleanup occurs after the first event in an earlier era, this is not captured in this analysis.
- This analysis considers the current set of contaminated sites in Delaware. However, in the future, and particularly by the late century, it is possible that this set will change due to both new sites developing and remediation actions being undertaken at current sites.
- Clean up costs are used as a proxy for the damages that would occur for an unmitigated release event. We do not measure the potential health risks associated with release events, which could be significant. These risks are likely to disproportionately affect low income households, given the historical close proximity of low income residential areas to industrial sites. Ecosystem damages from releases are also not included in the analysis.

CHAPTER 4 | HEALTH IMPACTS (DHSS)

The Delaware Department of Health and Social Services (DHSS) is responsible for providing services in support of the health and wellbeing of Delaware residents. To maintain that mission, it could be helpful for DHSS to understand how climate change affects existing (or drives new) public health concerns. Climate change may affect public health in a number of ways, including:

1. **Heat related mortality and morbidity** in relation to higher average temperatures, longer heat waves, and warmer evening temperatures. Heat related mortality and morbidity impacts for at-risk populations are presented separately in this report.
2. **Lung and respiratory disease** cases and complications due to increases of low-level ozone production, resulting from higher temperatures.
3. **Allergens and mold** production on respiratory illnesses and pre-existing health conditions, with a longer growing season.
4. **Vector-borne disease cases**, both confirmed and possible, from mosquito and ticks, due to longer breeding seasons and warmer winters.

The majority of health impacts are measured in this analysis terms of fatal risk related to increasing mortality rates. As shown in **Table 4-1**, lung and respiratory disease impacts are the largest among the health categories throughout the century under both representative concentration pathways (RCPs).[69] However, impacts related to heat related mortality and morbidity and vector-borne disease grow increasingly significant over the century.

TABLE 4-1. ANNUAL STATEWIDE ECONOMIC IMPACTS TO HEALTH CATEGORIES ($MILLION)

Figures represent total statewide impacts by RCP for temperature and precipitation-based impacts, reported in millions of dollars (2019). For further information on each category, please see Chapters 4.1 through 4.4.

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
4.1	Heat related mortality and morbidity	$7.8	$6.2	$15	$12	$110	$24
4.2	Lung and respiratory disease	$39	$23	$66	$38	$190	$82
4.3	Allergens and mold[a]	$0.006	$0.006	$0.010	$0.009	$0.018	$0.010
4.4	Vector-Borne Disease Cases	$11	$10	$20	$16	$44	$23

Notes:
a. Chapter 4.3 also includes illustrative impact estimates for mold impacts due to coastal flooding (from storm surge). See Table 4-10 for details.

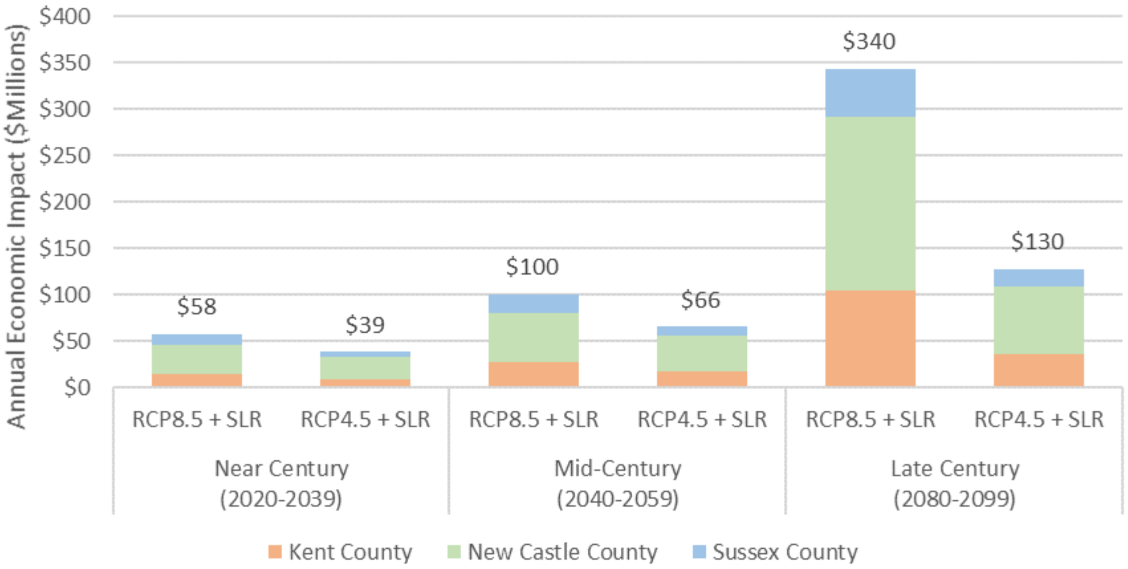
---

[69] Two different RCPs were considered in this analysis, corresponding to different emissions scenarios. Chapter 2.1 provides further details.

Figure 4-1 shows impacts by county. New Castle County, the county with the highest population, is expected to incur the highest impacts. Note we did not include any sea level rise (SLR) or storm surge related impacts to Delaware populations in this chapter, but the potentially fatal risk of storm surge was considered in the Public Safety chapter (Chapter 7).

FIGURE 4-1. HEALTH ECONOMIC IMPACTS BY COUNTY

Totals represent temperature and precipitation-based impacts (RCP8.5 or RCP4.5). Values are reported in 2019 dollars.



4.1 HEAT RELATED MORTALITY AND MORBIDITY

Heat related mortality and morbidity in relation to higher average temperatures, longer heat waves, and warmer evening temperatures

High-temperature days are projected to occur more frequently and reach more extreme temperatures over the course of this century, and exposure to extreme heat can impact people's health. High temperatures can reduce the body's ability to regulate internal temperatures, cause heat exhaustion or heat stroke, exacerbate existing medical problems, and lead to death. The first three effects constitute categories of morbidity, or health impacts that do not cause mortality.

Methods:

Heat-related mortality was estimated for approximately 100 cities in the U.S. through a Climate Change Impacts and Risk Analysis-sponsored study.[70] As the Climate Change Impacts and Risk Analysis study did not include any cities in Delaware, we pooled results from three cities close to Delaware that share similar latitude and geography to apply to Delaware cities: Washington, D.C., Baltimore, and Philadelphia.

Location-specific rates of mortality associated with temperature changes can vary based on a range of factors. These factors include baseline climate. Baseline temperature correlates with building and infrastructure accommodations to high temperatures (in hotter areas buildings are designed to shed heat and are more likely to be equipped with air conditioning). Baseline temperature and humidity also correlate with the body's acclimatization to high heat, as higher temperature and humidity lessen the body's ability to dissipate heat stress. Using cities with similar latitude and geography can best approximate the baseline temperature and humidity in Delaware, providing the best match for Delaware urban areas. These effects are limited to urban populations, and therefore we include the populations of the largest city in each county in Delaware (Dover, Seaford, and Wilmington). We calculate average per-capita extreme temperature mortality for the three cities included in the Climate Change Impacts and Risk Analysis for each era and RCP and scale those per-capita estimates to the populations for the three Delaware cities. Estimates for the city population represent the entire economic impact for the counties in which they are located. The valuation of mortality risk adopts a standard value of statistical life (VSL) approach – here we use the U.S. EPA VSL values used in U.S. EPA (2017), with the methods further documented in U.S.EPA (2018).[71]

Heat related morbidity is less well understood, but existing research suggests it has a much smaller total economic value. We developed estimates of the morbidity implications of heat stress by using two studies conducted for New York State, Lin et al. (2012) [72] and Knowlton et

---

[70] Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, M. Duckworth, and L. Deck, 2014: Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. *Climatic Change*, doi: 10.1007/s10584-014-1154-8, as extended by EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001, Chapter 5, Extreme Temperature Mortality.

[71] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001, Chapter 5, Extreme Heat Mortality. U.S. EPA 2018, Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CD) User's Manual, see page H-4. Document available here: https://www.epa.gov/sites/production/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

[72] Lin, S., Hsu, W.H., Van Zutphen, A.R., Saha, S., Luber, G. and Hwang, S.A., 2012. Excessive heat and respiratory hospitalizations in New York State: estimating current and future public health burden related to climate change. Environmental health perspectives, 120(11), pp.1571-1577.

al. (2006)[73], which provide changes in morbidity and mortality, respectively, for heat-related outcomes. The economic impact estimates for morbidity are assumed to be proportional to the mortality impacts, based on a linkage we generated between the Lin et al. (2012) morbidity results for New York City and the Knowlton et al. (2006) mortality results for New York City. We used this relationship between morbidity and mortality to estimate heat-related morbidity impacts in Delaware for the same three cities we consider in the heat-related mortality estimate. Valuation is based on hospitalization stay costs, which is consistent with the valuation methods in Lin et al. (2012). Costs were adjusted to 2019 dollar-years.

Heat related mortality and morbidity on at risk populations

We subcategorize the mortality and morbidity estimates by gender and socioeconomic status. The vulnerable population, women and low-income, are identified as at-risk based on demographic subpopulation analyses from Lin et al. (2012). Low-income is defined as income below 200 percent of the poverty line, as estimated by the U.S. Census Bureau American Community Survey for 2012-2016.[74] We report economic impacts for each vulnerable population, using the same strategy as the general mortality and morbidity valuation. The low-income and gender categories are not mutually exclusive, so it would not be appropriate to total across these sub-categories. In addition, there is some evidence that other populations may be at heightened risk for air pollution health effects (see, for example, Di et al. 2017[75]), but the income and gender categories are the groups that could be readily assessed for this analysis. Note that this category assumes status quo access to cooling centers.

The data sources used in this analysis are summarized in **Table 4-2**.

TABLE 4-2. HEAT RELATED MORTALITY AND MORBIDITY ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Per capita mortality	For three cities near Delaware, for each RCP and era	Mills, D., Schwartz, J., Lee, M. Sarofim, M., Jones, R., Lawson, M. Duckworth, M. and Deck, L. 2014. Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. Climatic Change, 131, 83-95.
Population projections	2010-2100, by county	U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.
New York City morbidity	Heat-related hospitalizations and hospitalization costs	Lin, S., Hsu, W.H., Van Zutphen, A.R., Saha, S., Luber, G. and Hwang, S.A. 2012. Excessive heat and respiratory hospitalizations in New York State: estimating current and future public health burden related to climate change. Environmental health perspectives, 120(11), 1571-1577.
New York City mortality	Heat-related mortality	Knowlton, K. Lynn, B., Goldberg, R.A., Rosenzweig, C., Hogrefe, C., Rosenthal, J.K., and Kinney, P.L. 2006. Projecting Heat-Related Mortality Impacts Under a Changing Climate in the New York City Region. American Journal of Public Health, 97(11), 2028-2034.
Population demographics	2012-2016 average, by county	U.S. Census Bureau American Community Survey for 2012-2016.

---

[73] Knowlton, K. Lynn, B., Goldberg, R.A., Rosenzweig, C., Hogrefe, C., Rosenthal, J.K., and Kinney, P.L., 2006: Projecting Heat-Related Mortality Impacts Under a Changing Climate in the New York City Region. *American Journal of Public Health*, 97(11), pp. 2028-2034.

[74] The relevant Census Bureau data table can be found here: https://data.census.gov/cedsci/table?q=s1701&tid=ACSST5Y2016.S1701&moe=false&hidePreview=false

[75] Di Q, Wang Y, Zanobetti A, Wang Y, Koutrakis P, Choirat C, Dominici F, Schwartz JD. 2017. Air Pollution and Mortality in the Medicare Population. The New England Journal of Medicine 376(26):2513-2522.

Results:

As shown in **Table 4-3**, economic impacts of heat-related mortality are projected to be significantly larger than those from heat-related morbidity. Total economic impact associated with heat-related health impacts are projected to more than triple between near century and late century under RCP4.5 and to increase by 10 times over this same period under RCP8.5. Wilmington is projected to have the largest damages, driven by a larger population than Dover and Seaford.

TABLE 4-3. ANNUAL ECONOMIC IMPACTS ASSOCIATED WITH HEAT-RELATED MORTALITY AND MORBIDITY DUE TO CLIMATE CHANGE ($MILLION)

Economic impacts are defined as the economic value, measured as VSL for mortality and cost of hospitalization for morbidity outcomes, above the baseline climate scenario (1986-2005). Results are reported in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Mortality	Kent County (Dover)	$2.9	$2.4	$6.2	$4.9	$49	$11
	New Castle County (Wilmington)	$4.4	$3.6	$8.3	$6.6	$57	$12
	Sussex County (Seaford)	$0.39	$0.31	$0.69	$0.55	$4.7	$1.0
	Delaware Total	**$7.8**	**$6.2**	**$15**	**$12**	**$110**	**$24**
Morbidity	Kent County (Dover)	$0.014	$0.011	$0.026	$0.021	$0.170	$0.037
	New Castle County (Wilmington)	$0.021	$0.017	$0.035	$0.028	$0.19	$0.042
	Sussex County (Seaford)	$0.002	$0.002	$0.003	$0.002	$0.016	$0.004
	Delaware Total	**$0.037**	**$0.029**	**$0.064**	**$0.051**	**$0.38**	**$0.083**
Mortality & Morbidity	Kent County (Dover)	$3.0	$2.4	$6.2	$5.0	$49	$11
	New Castle County (Wilmington)	$4.5	$3.6	$8.3	$6.6	$57	$12
	Sussex County (Seaford)	$0.39	$0.32	$0.69	$0.55	$4.7	$1.0
	Delaware Total	**$7.8**	**$6.2**	**$15**	**$12**	**$110**	**$24**

Table 4-4 shows that impacts grow similarly across the century for at-risk populations (women and low-income individuals), with economic impacts reaching $56 million by late century under RCP8.5 for women, and $32 million for low-income individuals.

TABLE 4-4. ANNUAL ECONOMIC IMPACTS ASSOCIATED WITH HEAT-RELATED MORTALITY AND MORBIDITY FOR AT-RISK POPULATIONS DUE TO CLIMATE CHANGE ($MILLION)

Economic impacts are defined as the economic value, measured as VSL for mortality and cost of hospitalization for morbidity outcomes, above the baseline climate scenario (1986-2005). Results are reported in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Mortality	Women	$3.9	$3.2	$7.7	$6.1	$56	$12
	Low-income individuals	$2.2	$1.8	$4.4	$3.5	$32	$7.0
Morbidity	Women	$0.02	$0.02	$0.03	$0.03	$0.19	$0.04
	Low-income individuals	$0.01	$0.01	$0.02	$0.02	$0.11	$0.02
Mortality & Morbidity	Women	$4.0	$3.2	$7.7	$6.1	$56	$12
	Low-income individuals	$2.2	$1.8	$4.4	$3.5	$32	$7.0

Note: Low-income individuals are defined as having income at or below 200 percent of the poverty line, as estimated by the U.S. Census Bureau. As noted in the text, women and low-income individuals are not the only populations which may be considered to be at heightened risk for air pollution health effects but are the groups most readily assessed for this analysis. The two identified vulnerable groups are not mutually exclusive, and therefore, results should not be summed.

Limitations:

- We are unaware of any current epidemiological literature that directly estimates heat mortality effects in Delaware's urban areas or in other Delaware locations. As a result, we use an epidemiological function for impacts estimated in other cities in the Mid-Atlantic region. The uncertainties introduced by this use of heat sensitivity for populations and locations outside of Delaware are unknown.
- Our results use Delaware-specific, all-cause mortality data to characterize the appropriate baseline incidence inputs for the extreme temperature mortality function we apply. Additional data available from the Delaware Department of Health and Social Services provides estimates of historical incidence of heat stress mortality in Delaware. Our analysis was not adjusted or calibrated to historical extreme temperature mortality incidence data for Delaware for two reasons: (1) historical incidence is available only for cases where extreme temperature could be positively identified as the primary cause of death, while the epidemiological function we apply is designed to be applied to data where extreme temperature is also a secondary factor associated with other causes; and (2) extreme temperature historical incidence data is for total populations for each county in Delaware, while our analysis is limited to urban areas.
- Some literature exists to suggest that extreme heat-related health impacts may not be limited to urban areas, and may actually be of comparable magnitude in non-urban areas

(see Madrigano et al. 2015).[76] This research suggests our estimates could understate extreme temperature mortality and morbidity in Delaware, given that our estimates only consider one urban area in each county.

- We assume proportional impacts to all demographic groups. Our estimates of impacts for at-risk populations are likely conservative, in that it is likely that low-income populations may be more susceptible to heat-related mortality and mortality, owing to a lower baseline health status and reduced access to quality health care and to air conditioning.[77] Improved health status and access to health care and air conditioning could mitigate the worst effects of heat stress.
- We rely on population demographics from the U.S. Census American Community Survey for 2012-2016.[78] In our projections of economic impacts, we assume population growth is proportional for all demographic groups. As noted in Chapter 2.1, overall population growth estimates, by county, are from the U.S. EPA Integrated Climate and Land Use Scenarios version 2.[79]

---

[76] Jaime Madrigano, Darby Jack, G Brooke Anderson, Michelle L Bell and Patrick L Kinney. (2015). Temperature, ozone, and mortality in urban and non-urban counties in the northeastern United States. Environmental Health 14(3), available at http://www.ehjournal.net/content/14/1/3

[77] See, for example, Eisenman et al. 2016. Heat Death Associations with the built environment, social vulnerability, and their interactions with rising temperature. Health and Place. 41:89-99 and Knowlton K, Rotkin-Ellman M, King G, et al. The 2006 California heat wave: impacts on hospitalizations and emergency department visits. Environmental Health Perspectives. 2009; 117(1):61–67

[78] American Community Survey data are available at: https://www.census.gov/programs-surveys/acs

[79] Population projection documentation is available at this link https://www.epa.gov/iclus The relevant publication is EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios version 2. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

4.2 LUNG AND RESPIRATORY DISEASE

Lung and respiratory disease cases and complications due to increase of low-level ozone production resulting from higher temperatures

As temperatures increase, ground-level ozone concentrations are expected to increase across the U.S, owing to the role temperature plays in accelerating the formation of ground-level ozone from nitrogen dioxide and volatile organic compounds in the atmosphere. Exposure to elevated levels of ozone results in lung and respiratory complications as well as premature deaths, as modeled by Fann et al. (2015).[80]

Methods:

Premature mortality associated with the increase of low-level ozone production (due to higher temperatures in Delaware) is extrapolated from the results of Fann et al. (2015), as extended by U.S. EPA (2017). The U.S. EPA study projects pre-mature mortality for two of the three requested time periods, but for only two General Circulation Models (GCMs), due to very high computational demands.[81] The two GCMs do represent a wide range of temperature outcomes for Delaware, with one providing one of the lowest and the other providing one of the highest available temperature forecasts. The study estimates future ozone levels based on projected changes in temperature and incorporates a baseline anthropogenic emissions estimate for an 11-year base period centered on the year 2000. Mortality endpoints are valued using U.S. EPA's standard valuation assumptions (from the BenMAP model[82]). Morbidity outcomes are not modeled in this study; however, we expect mortality to account for the vast majority of economics damages because of the high value associated with avoiding premature mortality risk.

Fann et al. do not provide estimates for the near century period, therefore near-century damages were calculated using a linear interpolation from the baseline period (2000) and mid-century (2050) values.

The data sources used in this analysis are summarized in **Table 4-5**.

TABLE 4-5. LUNG AND RESPIRATORY DISEASE ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Ozone related premature deaths	By county, for 2050 and 2090 eras	U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.
Value of statistical life	For 2050 and 2090, scales with projected GDP per capita	U.S. EPA. 2018. Documentation for the BenMAP air pollution benefits estimation tool.

---

[80] Fann, N., C.G. Nolte, P. Dolwick, T.L. Spero, A. Curry Brown, S. Phillips, and S. Anenberg, 2015: The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030. *Journal of the Air & Waste Management Association*, **65**, 570-580. http://dx.doi.org/10.1080/10962247.2014.996270

[81] Note that the eras in Fann et al. differ slightly from the eras used elsewhere. Air Quality eras in Fann et al. and therefore in this impact category analysis, were defined as follows: 2050 (2045-2055) and 2090 (2085-2095).

[82] U.S. EPA 2018, Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CD) User's Manual, see Appendix H for valuation approach and VSL methodology. Document available here: https://www.epa.gov/sites/production/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

Results:

Excess ozone-related pre-mature deaths for Delaware in the mid-century and late century are summarized by county and as a state total in **Table 4-6.** Excess deaths are compared to the modeled baseline era (an 11-year period centered on the year 2000). Note that while "fractional deaths" cannot actually occur, the estimates in **Table 4-6** reflect the calculation of the statistical risk of premature mortality compared to the baseline period. The results show an increase over time that is faster for the higher temperature RCP8.5 scenario compared to the RCP4.5 scenario. Estimates are higher for the more populous New Castle County, as expected.

TABLE 4-6. EXCESS OZONE-RELATED PREMATURE DEATHS COMPARED TO BASELINE DUE TO CLIMATE CHANGE

Excess mortality compared to baseline period (11-year period centered on the year 2000 era). Results are reported as risks of premature mortality (excess deaths) per year and are averaged over 2 GCMs. Values may not sum due to rounding.

	MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	1.2	0.6	2.5	1.1
New Castle County	2.4	1.7	6.5	2.9
Sussex County	1.3	0.6	2.5	1.0
Delaware Total	**4.9**	**2.8**	**11.5**	**5.0**
Note: The study on which these estimates are based did not estimate premature mortality for the Near Century period, so no value is reported here.				

The value of excess premature deaths in each Delaware county is summarized in **Table 4-7**. Valuation is based on the projected statistical risk of premature mortality and VSL in each era ($13.4 million in 2050 and $16.4 million in 2090).

TABLE 4-7. ANNUAL ECONOMIC IMPACTS ASSOCIATED WITH EXCESS OZONE-RELATED DEATHS DUE TO CLIMATE CHANGE ($MILLION)

Economic impacts are defined as the willingness to pay to avoid mortality risk, using a VSL valuation for excess deaths, above the baseline period (an 11-year period centered on the year 2000). Results are reported in millions of dollars (2019) per year and averaged over 2 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$9.4	$4.5	$16	$7.4	$41	$19
New Castle County	$20	$14	$33	$23	$110	$47
Sussex County	$10	$4.4	$17	$7.4	$41	$16
Delaware Total	**$39**	**$23**	**$66**	**$38**	**$190**	**$82**
Note: Near century economic impact estimates were not provided in the study on which these results are based. The near century estimates reported here are based on linear interpolation between the 2000 base period and the mid-century estimates.						

Limitations:

- Fann et al. (2015) only project mortality effects for two GCMs (CESM, GISS-E2) due to high computational demands.
- The study does not model morbidity effects of increased ground-level ozone concentrations. Prior analyses of air pollution impacts indicate that the economic impact of morbidity is between 2 and 3 percent of the economic impacts attributed to mortality impacts (see U.S. EPA 2011).[83] Therefore, in this category, adding morbidity effects of increased ozone could increase the overall economic impact estimates by no more than 5 percent.

---

[83] See the U.S. EPA report The Costs and Benefits of the Clean Air Act: 1990-2020, at https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-report-documents-and-graphics. In particular, see page 19 of the summary report: https://www.epa.gov/sites/production/files/2015-07/documents/summaryreport.pdf

4.3 ALLERGENS AND MOLD

Allergen and mold production on respiratory illnesses and pre-existing health conditions with a longer growing season

Methods:

Allergens

Climate change has been shown to extend growing seasons and, by extension, the pollen production season for many plant species, including those responsible for the most prevalent types of allergic pollen (e.g., trees, grasses, and some weeds) (see Anenberg et al. 2017 and Neumann et al. 2019 for a review of relevant literature). There is also limited evidence that climate change can increase the total production of pollen during the season. Extensive epidemiological evidence exists for several pollen types, in locations around the U.S. and in Europe, that quantify how increased pollen production and exposure leads to increases in respiratory problems, in particular, emergency department visits for asthma attacks. More limited evidence exists concerning links to other health effects, or to increased use of over-the-counter medicines. These other non-quantified impacts may have a larger economic impact than the more readily quantifiable effects and were not included in this analysis.

The basis for the allergen component of this work is a direct application of Neumann et al. (2019), a U.S. EPA sponsored study that conducted detailed modeling of the impact of climate on pollen season length for oak, birch, and grass pollens; the impact of changes in season length on pollen exposure; and the impact of pollen exposure on the rate of asthma emergency department visits.[84] From the Neumann et al. results, we used the health incidence results, provided nationally for 50km x 50km grid cells, for all future projection scenarios but developed a grid-weighted results disaggregation for the three counties in Delaware. Estimates presented here are relative to a climate baseline of 1986-2005, but a 2010 baseline for population, because the 2010 population baseline was used in the underlying Neumann et al. study. For reference, the results presented here represent about one percent of the total estimated projected incidence for the multi-state Northeast region in Neumann et al. (2019). This is consistent with Delaware accounting for about one percent of the population in the multi-state Northeast region in 2010.

The valuation method for an asthma-related emergency department visit used here is consistent with that used in Neumann et al. (2019), and in U.S. EPA (2018),[85] with updates to 2019 dollars. Valuation for asthma-related emergency department visits uses a cost-of-illness estimate of $528 per visit. The cost of illness estimate reflects only the direct (medical cost) valuation of economic impact and omits potential indirect costs such as lost work productivity or school time associated with emergency department visits. It also omits other effects of aeroallergen exposure, such as increased expenditures on over-the-counter medications to treat the effects of allergic responses.

---

[84] Neumann JE, Anenberg SC, Weinberger KR, et al. Estimates of Present and Future Asthma Emergency Department Visits Associated with Exposure to Oak, Birch, and Grass Pollen in the United States. *Geohealth*. 2019;3(1):11-27. doi:10.1029/2018GH000153

[85] U.S. EPA 2018, Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CD) User's Manual, see page H-4. Document available here: https://www.epa.gov/sites/production/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

Mold

The potential effect of more frequent floods on the production of mold, airborne mold spores, and mold fragments has been shown in some historical contexts (e.g., after Hurricane Katrina in the Gulf)[86] to be linked to an increased risk of respiratory disease.

We are not aware of any quantitative analysis that provides a basis for reliably projecting changes in respiratory illnesses associated with mold exposure, as potentially amplified by climate change. However, there are many studies that note a strong conceptual and epidemiological link between mold and respiratory illness. For example, in 2011, the Institute of Medicine of the National Academy of Sciences published a report on *Climate Change, the Indoor Environment, and Health*; which included a chapter on the link between climate change and the presence of dampness, moisture, and flooding.[87] They found there was sufficient evidence of an association between mold and the following respiratory symptoms: upper respiratory (nasal and throat) tract symptoms, coughing, hypersensitivity pneumonitis in susceptible persons, wheezing, and asthma symptoms in sensitized persons. Almost all reviews refer back to one study, which looked at mold concentrations (not health effects) in about 20 homes after the Hurricanes Katrina and Rita; both storms occurred during the 2005 hurricane season.[88] One of the more compelling studies cited for an area near the Delaware region (Nguyen et al. 2010), found statistically significant positive associations between current asthma prevalence and the presence of mold.[89] The research was completed via a telephone survey of New York State residents; however, the results were based on self-reported conditions, assessed only the presence or absence of mold (with no mention of the source), and did not control for the level of mold exposures. A more recent review (D'Amato et al. 2020) concludes that while there is "some evidence" that climate change may increase the severity of indoor and atmospheric mold exposures, "the magnitude of the increase of houses affected by mold and their effects on respiratory health are unclear."[90]

Our analysis utilizes a simple scalar of baseline morbidity impacts of mold exposure, provided by the Delaware Department of Health and Social Services, using the ICD-9 and ICD-10 codes that capture mold-related disease incidence in historical periods.[91] As no cases were reported prior to 2010, we use the annual average from 2010-2015 to represent the baseline period, with the assumption that prior to 2010 caregivers were unlikely to recognize a mold-related case. The multiplier used to scale the baseline incidence is a measure of "significant flooding events" from precipitation and storm surge events. For coastal events, we use the change in frequency of the

---

[86] Rao CY, Riggs MA, Chew GL, et al. Characterization of airborne molds, endotoxins, and glucans in homes in New Orleans after Hurricanes Katrina and Rita. *Appl Environ Microbiol*. 2007;73:1630-1634.

[87] Institute of Medicine 2011. *Climate Change, the Indoor Environment, and Health*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13115.

[88] Rao CY, Riggs MA, Chew GL, et al. Characterization of airborne molds, endotoxins, and glucans in homes in New Orleans after Hurricanes Katrina and Rita. *Appl Environ Microbiol*. 2007;73:1630-1634.

[89] Nguyen T, Lurie M, Gomez M, Reddy A, Pandya K, Medvesky M. 2010. The National Asthma Survey–New York State: Association of the home environment with current asthma status. *Public Health Reports* 125(6):877-887.

[90] Gennaro D'Amato, Herberto Jose Chong-Neto, Olga Patricia Monge Ortega, Carolina Vitale, Ignacio Ansotegui, Nelson Rosario, Tari Haahtela, Carmen Galan, Ruby Pawankar, Margarita Murrieta-Aguttes, Lorenzo Cecchi, Christian Bergmann, Erminia Ridolo, German Ramon, Sandra Gonzalez Diaz, Maria D'Amato, Isabella Annesi-Maesano. 2020. The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens *Allergy: The European Journal of Allergy and Clinical Immunology*, 2020;75:2219–2228. DOI: 10.1111/all.14476

[91] DHSS used ICD10 code Z77.120 and ICD9 code V87.31, representing, "Contact with, and (suspected) exposure to, mold (toxic)."

current 1-percent storm surge, by county. The change in storm surge is based on the analysis conducted by Marsooli et al. (2019), which considered future changes to storm surge frequency, though we used data specific to Delaware counties.[92] For this analysis, there is no available literature to connect flood levels to mold disease incidence. Instead, the available evidence suggests that elevated mold exposure and disease incidence is connected to hurricane and storm surge events. The Marsooli et al. study provides an event-based estimate of the frequency of a 1-percent hurricane storm surge event, which is suitable for this analysis, but because the results are limited to the 1-percent event, and to a single time period (late century), we do not use Marsooli et al. in other storm surge flood analyses in this report. The late century frequency result is interpolated linearly to the near century and mid-century periods.[93]

For precipitation events, which lead to inland flooding, we use the statewide change in frequency of the 24-hour 2-inch total precipitation rainstorm event. The change in frequency is a ratio of forecast to historical (baseline) event frequency, and is based on results reported in Chapter 4, Table 4.1 in the 2014 Delaware Climate Change Impact Assessment; this change in extreme precipitation event was also used as a key indicator of urban flood risk in a U.S. EPA-sponsored study of the impacts of climate change on urban drainage systems.[94]

Valuation of the health effects is complicated by two issues: (1) The reported historical baseline incidence of this health effect is so small, both in Delaware and nationally, that no medical cost-of-illness information can be provided from public health insurance charge databases without revealing confidential information; (2) The health effects of mold are likely an unknown combination of several health effects. As a result, we used the same health effect valuation as used for aeroallergens, based on the cost of an emergency department visit for an asthma attack. Due to the large uncertainties in estimating effects of climate change on health effects from mold exposure, and the difficulty in reliably connecting hurricane frequency with mold exposure, the results presented here for hurricane-linked exposures are for illustrative purposes only and are not carried forward in the chapter and overall report-level economic impact summaries.

The data sources used in this analysis are summarized in **Table 4-8**.

---

[92] Reza Marsooli, Ning Lin, Kerry Emanuel, and Kairui Feng, 2019. Climate change exacerbates hurricane flood hazards along U.S. Atlantic and Gulf Coasts in spatially varying patterns. *Nature Communications*. 10:3785, DOI:10.1038/s41467-019-11755-z

[93] Note that unlike other storm surge analyses, the event-based frequency estimate allows us to generate a scalar for hurricane frequency that is applied to the annual mold disease incidence, resulting in an annual estimate of mold disease for future periods. Other analyses rely on flood mapping of storm surge and which at this time cannot be adjusted for the full range of flood events across all return periods (that is, for other than the 1-percent storm).

[94] Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, 131, 97-109, doi:10.1007/s10584-013-1037-4, and Price, J., L. Wright, C. Fant, and K. Strzepek, 2014: Calibrated Methodology for Assessing Climate Change Adaptation Costs for Urban Drainage Systems. *Urban Water Journal*, **13**, doi:10.1080/1573062X.2014.991740, as extended by U.S. EPA 2017, Chapter 14.

TABLE 4-8. ALLERGENS AND MOLD ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Projected incidence of asthma emergency department visits associated with increased season length and pollen exposure in Delaware	U.S. EPA-sponsored study of the national impact of changes in pollen season length on health of exposed individuals; accessed the underlying grid-cell based results for grids in Delaware	Neumann, J.E., Anenberg, S.C., Weinberger, K.R., Amend, M., Gulati, S., Crimmins, A., Roman, H., Fann, N. and Kinney, P.L. 2019. Estimates of Present and Future Asthma Emergency Department Visits Associated with Exposure to Oak, Birch, and Grass Pollen in the United States. Geohealth. 3(1):11–27.
Mold exposure baseline health effect incidence	Incidence coded as ICD10 code Z77.120 and ICD9 code V87.31, representing, "Contact with, and (suspected) exposure to, mold (toxic)"	DHSS.
Storm surge and SLR stressor, 1-percent storm event	Change in frequency of the 1-percent storm surge event in each Delaware county	Marsooli, R., Lin, N., Emanuel, K. and Feng, K. 2019. Climate change exacerbates hurricane flood hazards along U.S. Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications. 10, 3785.
Change in frequency of 24-hour 2-inch precipitation event	Statewide estimate from prior work sponsored by DNREC	Delaware Climate Change Impact Assessment. 2014.
Medical cost-of-illness	Estimate of resource cost of an emergency department visit for an asthma attack	Neumann, J.E., Anenberg, S.C., Weinberger, K.R., Amend, M., Gulati, S., Crimmins, A., Roman, H., Fann, N. and Kinney, P.L. 2019. Estimates of Present and Future Asthma Emergency Department Visits Associated with Exposure to Oak, Birch, and Grass Pollen in the United States. Geohealth. 3(1):11–27.

Results:

The overall national effects of aeroallergens attributed to climate change in Neumann et al. (2019) are projected to be relatively small compared to other health impact categories and other overall impacts of climate change. The aeroallergen results reported here are roughly proportional to the population of Delaware relative to the U.S. population.

The mold economic impact results are also small relative to other health impact categories. There were only 11 cases of mold exposure reported in all of Delaware over the six-year period 2010 to 2015, suggesting the overall prevalence of mold-related morbidity is low, under-reported, or perhaps both. As shown in **Table 4-9**, impacts from inland flooding are expected to grow slowly through the projection period, although high precipitation events could increase in frequency by as much as 60 percent by the 2080-2099 period under RCP8.5, from the baseline period average of 2.1 times to 3.4 times annually.

Mold exposure from coastal events similarly is based on a relatively small baseline morbidity incidence, but could grow rapidly over time, as the 1-percent coastal storm surge event in the baseline period is expected to become an annual event by the late century period (see **Table 4-10**).

TABLE 4-9. ANNUAL ECONOMIC IMPACTS RELATED TO ALLERGENS AND INLAND FLOODING EXPOSURES TO MOLD DUE TO CLIMATE CHANGE

Economic impacts are defined as the cost of an emergency room visit for individuals acutely exposed to allergens and inland flooding exposures to molds (due to extreme precipitation), above the health incidence baselines (2010 for allergens, 2010-2015 for mold), averaged over 5 GCMs for allergens analysis, and using baseline extreme precipitation event data from the Delaware Climate Change Impact Assessment (2014) for mold. Measured in dollars (2019) per year. Values may not sum due to rounding.

		NEAR CENTURY (2020-2019)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Allergens	Kent County	$1,300	$1,400	$2,400	$2,100	$4,800	$2,400
	New Castle County	$2,300	$2,600	$4,600	$3,800	$8,500	$4,500
	Sussex County	$1,100	$1,200	$2,100	$1,800	$4,100	$2,100
	Delaware Total	**$4,700**	**$5,100**	**$9,100**	**$7,800**	**$17,400**	**$9,000**
Mold	Kent County	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000
	New Castle County	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000
	Sussex County	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000
	Delaware Total	**$1,200**	**$1,200**	**$1,200**	**$1,200**	**$1,600**	**$1,200**
Allergens and Mold	Kent County	$1,500	$1,600	$2,700	$2,300	5,100	$2,700
	New Castle County	$2,700	$3,000	$5,000	$4,300	$9,100	$4,900
	Sussex County	$1,600	$1,700	$2,600	$2,400	$4,900	$2,600
	Delaware Total	**$5,800**	**$6,300**	**$10,300**	**$8,900**	**$19,000**	**$10,200**

TABLE 4-10. ANNUAL ECONOMIC IMPACTS OF MOLD EXPOSURES DUE TO COASTAL FLOODING (1-PERCENT STORM SURGE)

Economic impacts are defined as the cost of emergency room visits for individuals acutely exposed to mold from coastal exposures, above the mold health incidence baseline (2010-2015). The results use Marsooli et al. (2019) to provide an estimate for the change in frequency of the 1-percent storm surge event in each Delaware county. The results are based on storm surge heights estimated by Marsooli et al. (2019) and are calculated using the intensity of levels of future storm surge events, above projected SLR, with extrapolations from the Late Century era back to the Near Century and Mid-Century eras. Measured in dollars (2019) per year. Values may not sum due to rounding. The results presented here are for illustrative purposes only.

	NEAR CENTURY (2020-2039)	MID-CENTURY (2040-2059)	LATE CENTURY (2080-2099)
Kent County	$1,800	$8,800	$18,000
New Castle County	$3,500	$18,000	$35,000
Sussex County	$4,400	$22,000	$44,000
Delaware Total	**$9,700**	**$48,000**	**$97,000**

Limitations:

- Estimates for allergen exposure reflect only the more readily quantifiable impacts of pollen on the rate of emergency department visits for asthma, and only for oak, birch, and grass pollens. Other types of pollen, such as ragweed, can also cause acute allergic responses, but the epidemiological literature on ragweed exposure leading to acute effects is confounded by the simultaneous occurrence of the ragweed pollen peak and the autumn start of the school year, resulting in inconclusive epidemiological evidence for ragweed. Since both the start of the school year, when children are exposed to a wide range of new infection sources, and the start of the ragweed season coincide, epidemiologic functions cannot reliably identify the cause of any increase in emergency department visits. In addition, more limited evidence exists concerning links to other health effects for all pollen types and to increased use of over-the-counter medicines. As noted in Neumann et al. (2019), these other impacts may have an even larger economic impact than the more readily quantifiable effects.
- Morbidity from mold exposures is likely a severely under-reported incidence in the historical baseline. It appears likely that medical practitioners would be hard pressed to attribute respiratory or other symptoms solely to mold exposure. Other literature suggests that mold may often be the source of asthma prevalence, asthma attacks, and other respiratory symptoms.
- There is little or no epidemiology or exposure severity-based quantitative literature on which to base a projection of mold-related morbidity incidence related to climate change. As a result, we apply a transparent scalar-based approach to provide illustrative results for this category of effects. The results for mold are exemplary of the possible magnitude of effect, but because of the lack of quantitative literature on this impact, the reported results should be interpreted as a best estimate.
- Data on the direct medical cost-of-illness, or indirect productivity loss, associated with mold-related morbidity is not currently available. As a result, we rely on an estimate of the cost-of-illness for asthma emergency department visits as a conservative, likely underestimated, value of the cost per case for this category. For both the pollen/allergen and the mold analysis, the exclusion of indirect (lost productivity) costs for emergency department visits likely underestimates the full cost, because an emergency department visit may imply indirect costs as well, such as lost work, school, or caregiver workdays. Consistent with other research, such as Neumann et al. (2019), and best practice for U.S. EPA climate change impacts and benefits analyses (see U.S. EPA 2017), we hold constant the real resource costs of an emergency department visit over time, which may also be a conservative assumption.

4.4 VECTOR-BORNE DISEASE CASES

Vector-borne disease cases, both confirmed and possible, from mosquito and ticks due to longer breeding seasons and warmer winters

The two most common vector-borne diseases in Delaware are West Nile virus, for mosquitoes, and Lyme disease, for ticks. Incidences for both diseases are projected to increase due to climate change as vector breeding seasons lengthen.

Methods:

West Nile Virus

The DHSS provided baseline incidences of West Nile virus (for 1995 to 2015) and Lyme disease (for 1995 to 2018) for Delaware by county, which is the starting point for both analyses. The West Nile virus analysis conducted is based on the U.S. EPA-sponsored Belova et al (2017) study.[95] The Belova et al. study models the increase in West Nile virus incidences by estimating a health impact function that relates incidence of West Nile neuroinvasive disease with temperature in the historical period of 2004-2010. The authors project estimates of temperature to 2050 and 2090 using five GCMs, and apply their model to estimate future West Nile neuroinvasive disease incidence. We average results for the five GCMs and linearly interpolate to estimate incidence and valuation for the near century era.

The Belova et al. study also provides a methodology for valuing additional cases, using medical cost-of-illness to treat the disease (an average cost of $41,391) and the standard U.S. EPA value of statistical life for valuing increases in mortality risk presented by the disease (approximately 6.5% of cases in the historical period resulted in death). The Belova study is the only currently available estimate, of which we are aware, of the impacts of climate change on West Nile virus incidence.

The Belova study reports average annual incidence of West Nile neuroinvasive disease of 0.129 cases for the baseline population in 2010 and baseline climate for the 1986-2005 period. DHSS data for the 1995 to 2015 period show an average annual number of cases of 1.90 cases. For the 2005 to 2015 period, approximating the 2010 population baseline used in Belova, the average annual DHSS case count is estimated to be 2.09. These large differences likely reflect site-specific characteristics of Delaware counties that are not accounted for in the national Belova study. We therefore chose to apply a calibration factor to the projected incidence estimates from Belova to adjust for this discrepancy.

Lyme disease

Lyme disease is prevalent in Delaware — the average annual Lyme incidence in the baseline period (1995-2013) was about 425 cases. Our analysis of Lyme disease is based on Couper et al. (2020) which provides functions for projecting Lyme disease incidence in six regions of the United States in response to changing climate.[96] The Couper et al. study is the only currently

---

[95] Belova, A., Mills, D., Hall, R., Juliana, A.S., Crimmins, A., Barker, C. and Jones, R. (2017) Impacts of Increasing Temperature on the Future Incidence of West Nile Neuroinvasive Disease in the United States. *American Journal of Climate Change*, **6**, 166-216. https://doi.org/10.4236/ajcc.2017.61010.

[96] Couper, L.I., MacDonald, A.J. and Mordecai, E.A., 2020. Impact of prior and projected climate change on U.S. Lyme disease incidence. *bioRxiv*.

available estimate of the impacts of climate change on Lyme disease. The model estimates future incidence as a function of average spring temperature, number of hot/dry days, cumulative temperature, total annual precipitation, and temperature variability. We calculate the baseline mean and standard deviations from DHSS data of county-level incidences, 1995 to 2013 (consistent with the baseline period used in Couper et al.) and forecast cases using the Couper et al. function for the Northeast Region, which includes Delaware, using climate variables (e.g., average spring precipitation, total annual precipitation, temperature variability) from six GCMs, relative to the 1995 to 2013 baseline defined in Couper et al. We report average results across the six GCMs.

Lyme disease incidences are valued using a direct and indirect cost of illness developed by Zhang et al. (2006).[97] Our literature review found four possible studies that could be used to estimate the economic impact of Lyme disease on afflicted individuals, but the Zhang study reflected the most comprehensive direct and indirect costs of illness; our finding is consistent with Mac et al. (2019), a recent literature review on this topic.[98] Zhang et al. found the average Lyme disease patient incurs $2,970 in direct medical costs and $5,202 in indirect medical costs, non-medical costs, and productivity losses in 2016. Adjusted to 2019 dollars, this represents a total direct and indirect cost of illness of $12,133 per incidence. Note that Zhang et al. considers a weighted average of costs, considering different costs associated with at least two levels of disease severity and weights based on incidence rates by severity.

The data sources used in this analysis are summarized in **Table 4-11**.

TABLE 4-11. VECTOR-BORNE DISEASE ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Baseline West Nile virus cases	1995 to 2015, by county	DHSS.
Baseline Lyme disease cases	1995 to 2013, by county	DHSS.
Cost of illness, West Nile virus	Includes VSL and morbidity costs	BenMAP (VSL) and Staples, J.E., Shankar, M.B., Sejvar, J.J., Meltzer, M.I. and Fischer, M., 2014. Initial and long-term costs of patients hospitalized with West Nile virus disease. The American journal of tropical medicine and hygiene, 90(3), pp.402-409.
Cost of illness, Lyme disease	Includes direct and indirect costs	Zhang, X., Meltzer, M. I., Peña, C. A., Hopkins, A. B., Wroth, L., and Fix, A. D. 2006. Economic impact of Lyme disease. Emerging infectious diseases. 12(4), 653.

Results:

Our analysis indicates that West Nile virus incidence is low relative to Lyme disease over the century, but the consequences are more serious. The incidence of West Nile virus is projected to

---

[97] Zhang, X., Meltzer, M. I., Peña, C. A., Hopkins, A. B., Wroth, L., & Fix, A. D. (2006). Economic impact of Lyme disease. Emerging infectious diseases, 12(4), 653.

[98] Mac S, da Silva SR, Sander B (2019) The economic burden of Lyme disease and the cost-effectiveness of Lyme disease interventions: A scoping review. PLoS ONE 14(1): e0210280. https://doi.org/10.1371/journal.pone.0210280.

increase with higher temperatures in Delaware but more slowly than for Lyme disease. As a result, the projected economic impact of West Nile virus incidence is about 10 percent, or less, than that for Lyme disease (see **Table 4-12**). The impact is lower for RCP4.5 than RCP8.5, as expected, because of the lower projected temperatures in the RCP4.5 scenario.

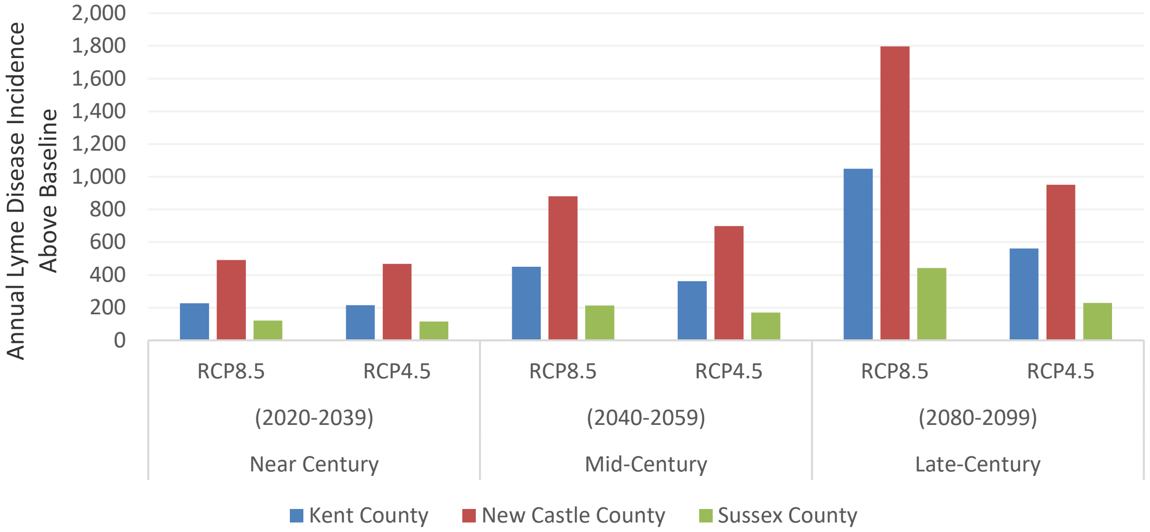
Lyme disease incidence, already high in Delaware, are projected to more than double between near century and late century under RCP4.5 and increase by nearly four times over the same period under RCP8.5 (see **Figure 4-2**). New Castle County, which has the highest population and highest baseline incidence of Lyme disease (roughly 60 percent of the total Lyme diseases cases reported in Delaware from 1990 to 2018), also has the highest number of projected cases and associated costs. Kent County is projected to continue to have the highest cases per capita (180 to 340 cases per 100,000 people in the late century under RCP4.5 and 8.5, respectively). Differences between the RCP4.5 and 8.5 scenarios are relatively small at the near to mid-century periods but diverge by late century.

TABLE 4-12. ANNUAL ECONOMIC IMPACTS FROM INCREASED VECTOR BORNE DISEASE INCIDENCE DUE TO CLIMATE CHANGE ($MILLION)

Economic impacts are defined as the value of additional morbidity and mortality (VSL), above the health incidence baselines (1995-2015 for West Nile Virus, 1995-2013 for Lyme disease to match the underlying model baselines) and above the baseline climate scenario (1986-2005), averaged over 5 GCMs (West Nile Virus) or 6 GCMs (Lyme). Measured in dollars (2019) per year. Values may not sum due to rounding.

		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
West Nile Virus	Kent County	$0.21	$0.15	$0.40	$0.28	$1.4	$0.46
	New Castle County	$0.42	$0.30	$0.80	$0.55	$2.7	$0.93
	Sussex County	$0.060	$0.043	$0.11	$0.08	$0.39	$0.13
	Delaware Total	**$0.70**	**$0.49**	**$1.3**	**$0.91**	**$4.5**	**$1.5**
Lyme Disease	Kent County	$2.7	$2.6	$5.5	$4.4	$13	$6.8
	New Castle County	$6.0	$5.7	$11	$8.5	$22	$12
	Sussex County	$1.5	$1.4	$2.6	$2.1	$5.4	$2.8
	Delaware Total	**$10**	**$9.7**	**$19**	**$15**	**$40**	**$21**
West Nile Virus & Lyme Disease	Kent County	$3.0	$2.8	$5.9	$4.7	$14.0	$7.3
	New Castle County	$6.4	$6.0	$11	$9.0	$25	$12
	Sussex County	$1.5	$1.5	$2.7	$2.1	$5.8	$2.9
	Delaware Total	**$11**	**$10**	**$20**	**$16**	**$44**	**$23**

FIGURE 4-2. ANNUAL LYME DISEASE INCIDENCE ABOVE THE HEALTH INCIDENCE BASELINE (1995-2013 AVERAGE) AND THE BASELINE CLIMATE SCENARIO (1986-2005) DUE TO CLIMATE CHANGE



Limitations:

- The Lyme disease health impact estimation function from Couper et al. is calibrated to climate variables representing the entire Northeast region; applying this function to Delaware may have introduced bias which would require further investigation (i.e., a degree of warming in Delaware may have more or less impact than the average impact of a degree of warming across the Northeast).
- The cost of illness for Lyme disease is based on a national estimate, but costs in Delaware may be more or less than the national average.
- West Nile virus estimates reflect a large calibration factor for baseline case counts (roughly a factor of 15) relative to the Belova study estimate. We trust the local scale incidence results to a much higher degree than the older and national scale Belova study estimate; however. this calibration has a large influence on the overall results. The large calibration factor likely reflects inaccuracies in the national estimate as applied to Delaware, rather than a specific over- or under-estimation bias in the results reported here, but any large calibration factor introduces additional uncertainty in the estimation.

CHAPTER 5 | TRANSPORTATION IMPACTS (DELDOT)

The Delaware Department of Transportation (DelDOT) is responsible for providing safe and reliable transportation infrastructure in the state. To maintain that mission, DelDOT may want to understand how climate change impacts the integrity of the state's infrastructure. Climate change is likely to affect various aspects of the transportation sector, including:

1. **Structure and stability of roadways, bridges, and railways**, related to prolonged high heat events, extreme weather events, and increased precipitation.
2. **High and significant hazard dams** and the impacts of more frequent and intense precipitation events.
3. **Culvert damage and road closures from flooding**, related to high precipitation and extreme weather events.
4. **Road closures from coastal flooding,** including high tide flooding, extreme weather events, and sea level rise (SLR).

Impacts in this sector are measured primarily through direct expenses for: (1) infrastructure repair and replacement; and (2) delay costs for passengers and freight while road, rail, and bridges are inaccessible. As described in further detail in the following sections, transportation impacts generally assume reactive adaption — that is, continued maintenance and repair at current levels.

Table 5-1 presents statewide impacts by impact category. Impacts in the transportation sector are dominated by road closures from coastal flooding (i.e., high tide flooding), which reach over a half billion dollars in annual impacts by the end of the century under both representative concentration pathways (RCPs). Chapter 2.1 provides further details on the RCPs used.

TABLE 5-1. ANNUAL STATEWIDE ECONOMIC IMPACTS TO TRANSPORTATION CATEGORIES ($MILLION)

Figures represent total statewide impacts by RCP (for categories impacted by changes in temperature and precipitation) or by era only (for categories impacted by SLR, excluding storm surge) in millions of dollars (2019). As this table presents annual impacts, storm surge impacts are not included, as such impacts are estimated on a per-event basis. For further information on each category, please see Chapters 5.1 through 5.4.

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
5.1	Roads, Rail, and Bridges structures	$58	$47	$77	$57	$160	$94
5.2	High and Significant Hazard Dams	$0.35	$0.18	$0.26	$0.14	$1.2	$0.22
5.3	Culverts and Road Closures	$5.7	$3.2	$2.0	$0.30	$25	$16
5.4	High Tide Flooding	$3.1		$25		$540	

Figure 5-1 shows the distribution of impacts by county. The majority of the impacts are projected to occur in New Castle County, where transportation infrastructure (repair costs) and population (delay cost) are most concentrated.

FIGURE 5-1. TRANSPORTATION ECONOMIC IMPACTS BY COUNTY

Totals represent temperature and precipitation-based impacts (RCP8.5 or RCP4.5) plus SLR impacts. As this figure presents annual impact values, totals do not include storm surge impacts, as such impacts are estimated on a per-event basis. Values are reported in 2019 dollars.

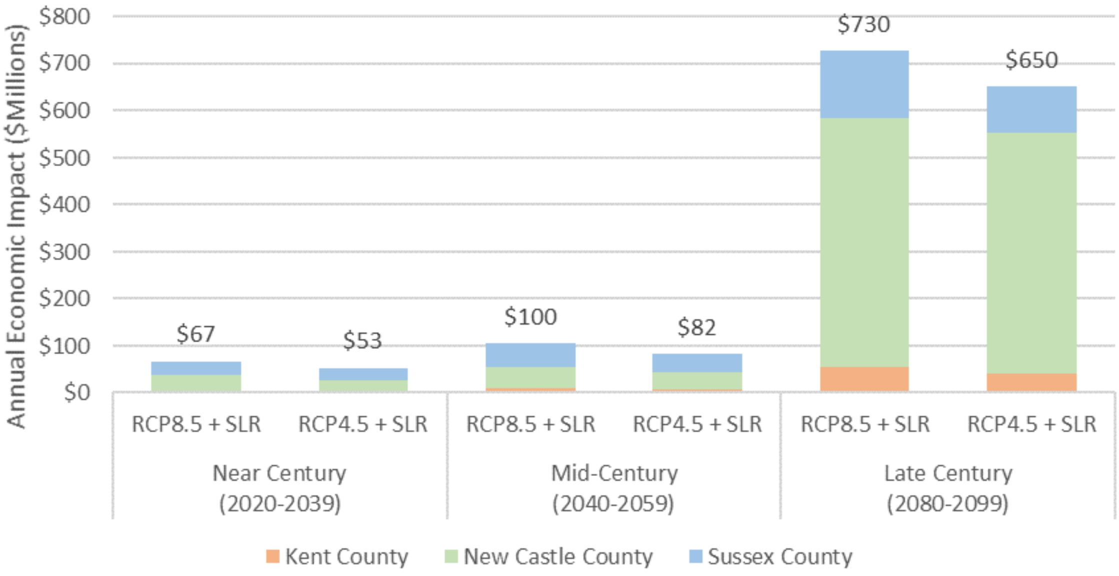


Table 5-2 shows the projected total impacts due to storm surge events for the high tide flooding impact category.

TABLE 5-2. STATEWIDE ECONOMIC IMPACTS TO TRANSPORTATION CATEGORIES FROM STORM SURGE EVENTS ($MILLION)

Impacts shown below result from 1-percent and 10-percent storm surge events, reported in millions of dollars (2019). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The below values represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year).

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		10% Storm	1% Storm	10% Storm	1% Storm	10% Storm	1% Storm
5.4	High Tide Flooding	$3.9	$18	$8.4	$24	$54	$71

5.1 STRUCTURE AND STABILITY OF ROADWAYS, BRIDGES, AND RAILWAYS

Prolonged high heat events, extreme weather events and increased precipitation on the structure and stability of roadways, bridges, and railways

Paved and unpaved roadways can be damaged by high temperatures and extreme precipitation events. Railways can be stressed by extreme temperature that causes rail expansion. Bridge supports and decks are susceptible to scouring and overtopping from high streamflow events.

Methods:

The methods used to assess impacts to roads, rail, and bridges are based on a series of infrastructure impact studies funded by the U.S. EPA. For road infrastructure, the U.S. EPA Climate Change Impacts and Risk Analysis work captures the effects of changes in temperature, precipitation patterns, and freeze-thaw cycles on paved roads and unpaved roads.[99] The methods used for capturing the climate change costs associated with these stressors build upon those detailed in Chinowsky et al. (2013)[100] and Neumann et al. (2014),[101] as applied in the U.S. EPA Climate Change Impacts and Risk Analysis (U.S. EPA 2017). More recently, these methods were updated in Neumann et al. (submitted),[102] to address the economic impacts for three adaptation response scenarios, which are described below.

First, for a "no adaptation" scenario, repair costs are incurred in response to events such as extreme temperature-induced road buckling or the washouts of unpaved roads during high precipitation events. In this "no adaptation" scenario, costs are incurred only up to an estimate of the current transportation agency's budget, sufficient to address necessary repair costs under the current climate. Repairs also require temporary road closures, which result in road user delays (passenger and freight). Delays are valued based on the lost value of user time, either individuals as passengers, or in the case of freight, using the value of lost production time. The economic estimates are based on U.S. DOT guidance on valuing lost time.[103] Once that budget is exhausted, roads can deteriorate, and additional user costs can incur – such as additional delays from reduced speeds on a rutted road, and/or an increased need for car repairs.

Second, under a "reactive adaptation" scenario, the budget constraint for repair costs can be exceeded in order to keep roads repaired to the current level of service. The excess repair costs then represent the cost of climate change. In all cases, the repairs are made in order to rebuild to prior conditions, with specifications dictated by the current climate. Road user delays are also incurred, from unexpected road closures to repair damaged infrastructure.

---

[99] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.

[100] Chinowsky P, Price J, Neumann J (2013) Assessment of climate change adaptation costs for the U.S. road network. Glob Environ Chang 23(4):764–773, http://www.sciencedirect.com/science/article/pii/S0959378013000514

[101] Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change,* 131, 97-109.

[102] James E. Neumann, Paul Chinowsky, Jacob Helman, Margaret Black, Charles Fant, Kenneth Strzepek, and Jeremy Martinich. Submitted: Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Submitted to Climatic Change.

[103] U.S. DOT. 2016b. Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. Downloaded from https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf

A third "proactive adaptation" scenario was also modeled for the U.S. EPA work, but was not used in the Delaware analysis. Proactive adaptation goes beyond reactive adaptation, adopting any measure that represents cost-effective investments in resilience. Given that only cost-effective measures are adopted (that is, measures that pass a benefit-cost test), some damage to roads from climate change still occurs, and requires repair costs to be incurred.

The estimates reported for the Delaware analysis are for the reactive adaptation scenario, meaning that the cost of climate change is represented by the future increase in road maintenance and repair budgets sufficient to repair all future road damages associated with climate change.

For railroads, we apply the results described in Chinowsky et al. (2019).[104] These methods account for the effects of track expansion and buckling during extreme heat events. Consistent with that literature, the scenario associated with buckling is not a derailment (which is rare) but rather the cost of freight or passenger delays associated with slowing or stoppage of trains in cases where extreme heat reaches a level where tracks may become damaged.

Estimates for the bridge sector were also drawn from the U.S. EPA Climate Change Impacts and Risk Analysis series of studies, which was originally based on Neumann et al. (2014) but has been updated using the methods from a forthcoming Strzepek et al.[105] paper. The method uses streamflows for over 70,000 catchments nation-wide from Wobus et al. (2017)[106], and common stream channel geometry to estimate flow velocities. Then, the flow velocities are used in a stressor-response relationship (known as a "fragility curve") calibrated to bridge age to determine the probability of damage or failure from pier scouring or deck overtopping (or both) during high flow events. Damages are repair costs and the cost of travel delays during bridge outages. Delays are estimated by using the re-routing distance to the next nearest bridge crossing, as identified in the National Bridge Inventory.[107] Note that the bridge inventory for Delaware was modified for this work to focus only on bridges over water bodies, and excludes both culverts and bridges over roadways, railways, or other non-water bodies.

We conducted a final step to adjust the road and rail inventories to be consistent with the most recent Delaware-specific data. For roads, the methods and sources described above yield a road network extent that is about 40 percent higher than from DelDOT sources. This difference could be attributable to the use of a grid network in the U.S. EPA study, and means that roads near the Delaware state border, but not in Delaware, could be incorrectly attributed to Delaware counties. For rail, the methods and sources described above yield a rail network that is about 40 percent smaller than DelDOT data – perhaps attributable to the same grid cell resolution issues noted for roads. The final DelDOT inventory indicates a statewide total of 8,889 road miles, and 382 rail miles. The calibration factors were estimated and applied at the county level.

---

[104] Chinowsky, Paul, Jacob Helman, Sahil Gulati, James Neumann, and Jeremy Martinich. 2019. "Impacts of climate change on operation of the US rail network". *Transport Policy*. 75: 183-191.

[105] Kenneth Strzepek, Paul Chinowsky, Jacob Helman, Margaret Black, James E. Neumann, Cameron Wobus, and Jeremy Martinich. A framework for estimating continental-scale climate change flood risk vulnerability and assessing adaptation options for bridge Infrastructure. (Working Paper)

[106] Wobus, Cameron, Ethan Gutmann, Russell Jones, Matthew Rissing, Naoki Mizukami, Mark Lorie, Hardee Mahoney, Andrew W. Wood, David Mills, and Jeremy Martinich. (2017). Climate change impacts on flood risk and asset damages within mapped 100-year floodplains of the contiguous United States. *Nat. Hazards Earth Syst. Sci.*, 17:2199–2211.

[107] U.S. DOT. 2017a. NBI ASCII Files 2017. Federal Highway Administration. Downloaded from https://www.fhwa.dot.gov/bridge/nbi/ascii2017.cfm on March 15, 2018.

The data sources used in this analysis are summarized in **Table 5-3**.

TABLE 5-3. ROADWAYS, BRIDGES, AND RAILWAYS ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Infrastructure inventory data	Rail: The primary source for the rail inventory was the National Transportation Atlas Database; only active main line and sub main line track were included in this analysis; the results are calibrated at the country scale for consistency with the most recent Delaware inventory information	U.S. Department of Transportation. 2015. National Transportation Atlas Database. Bureau of Transportation Statistics. https://www.michigan.gov/documents/deq/deq-rmd-wws-wwss12-pres1_390429_7.pdf
	Roads: State-level roads data from U.S. Department of Transportation (2008) and digitized road maps from Tele Atlas (2003), calibrated at the county scale for consistency with the most recent Delaware inventory information	Road inventory is described in Chinowsky P, Price J, Neumann J. 2013. Assessment of climate change adaptation costs for the U.S. road network. Glob Environmental Change. 23 (4):764-773. U.S. Department of Transportation, Federal Highway Administration. 2009. Highway Statistics 2008. Tele Atlas, 2003. Tele Atlas Dynamap Transportation, Version 5.2.
	Bridges: National Bridge Inventory as of 2017; the inventory is modified for this work to focus only on bridges over water bodies, limited to exclude both culverts and bridges over roadways, railways, or other non-water bodies	U.S. Department of Transportation. 2017. National Bridge Inventory ASCII Files. Federal Highway Administration. https://www.fhwa.dot.gov/bridge/nbi/ascii2017.cfm
Traffic and ridership data	Rail: Federal Railroad Administrations Office of Safety Analysis website data for highway-rail crossing data for all rail lines in the U.S.; the number of trains passing each crossing during the day was compiled based on the information received from railroad owners and operators	Traffic data is from U.S. Department of Transportation. 2016. Highway-Rail Crossing Inventory Data. Federal Railroad Administration, Office of Safety Analysis. https://safetydata.fra.dot.gov/OfficeofSafety/publicsite/downloaddbf.aspx Ridership data from U.S. Department of Transportation. 2017. Freight Analysis Framework Network. http://osavusdot.opendata.arcgis.com/datasets/560e1c2711f34aaf904fd8ab1f9333b9_0. Freight rail traffic data was supplemented to estimate bulk versus intermodal traffic using summary data from the American Association of Railroads. https://www.aar.org/data-center/rail-traffic-data/
	Roads: Road traffic from the Department of Transportation Freight Analysis Framework Network for paved primary and secondary roads; includes truck traffic; we derive estimates of traffic for tertiary roads using data from the Federal Highway Administration (2013) on average annual daily traffic	U.S. Department of Transportation. 2017. Freight Analysis Framework Network. http://osavusdot.opendata.arcgis.com/datasets/560e1c2711f34aaf904fd8ab1f9333b9_0 U.S. Department of Transportation, Federal Highway Administration. 2013. Highway Functional Classification Concepts, Criteria and Procedures.

Economic cost of traffic delays	Rail: For freight traffic, we follow the approach described in Chinowsky et al. (2017), based on Lovett et al. (2015) with an adjustment for the cost of fuel which varies by speed notch; for passenger rail, we assume that passengers would de-board trains that are stopped due to a buckling event and find an alternative mode of transportation to reach their destination, with an estimated total delay time of eight hours; to quantify the costs of passenger delay, we rely on U.S. Department of Transportation's 2016 guidance for the valuation of travel time in economic analysis	U.S. Department of Transportation. 2016. Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf Chinowsky, P., Helman, J., Gulati, S., Neumann, J. and Martinich, J. 2017. Impacts of climate change on operation of the U.S. rail network. Transport Policy. 75, 183-191. Lovett, A. H., Dick, C. T., and Barkan, C. P. 2015. Determining freight train delay costs on railroad lines in North America. Proceedings of Rail Tokyo.
	Roads and Bridges: Different sources are used for passenger and freight vehicles; for passenger vehicles, the approach follows that recommended in U.S. Department of Transportation (2016b) For freight vehicle travel, we rely on data from the National Cooperative Highway Research Program that are used as inputs to their Truck Freight Reliability Valuation Model (2016)	Passenger vehicles: U.S. Department of Transportation. 2016. Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf Freight vehicles: National Cooperative Highway Research Program. 2016. Report 824: Methodology for Estimating the Value of Travel Time Reliability for Truck Freight System Users. http://www.trb.org/Publications/Blurbs/174297.aspx

Results:

Of the three categories examined here, economic impacts to roadways are projected to be the largest, growing from a total of $30 to $40 million annually in the near century to a total of $60 to $110 million annually in the late century (see **Table 5-4**).

TABLE 5-4. ANNUAL ECONOMIC IMPACTS TO ROADWAYS FROM CLIMATE CHANGE ($MILLION)

Economic impacts are defined as repair and delay costs on paved and unpaved roads above the baseline climate scenario (1986-2005) costs. Impacts are measured in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$2.8	$3.2	$4.9	$4.2	$14	$6.0
New Castle County	$32	$22	$33	$21	$69	$47
Sussex County	$25	$23	$42	$34	$73	$35
Delaware Total	**$60**	**$49**	**$79**	**$59**	**$160**	**$88**

As shown in **Table 5-5**, impacts to bridge infrastructure are negative (or a reduction in damages relative to the modeled baseline period damages) for both the near century and mid-century periods, because in those scenarios, the peak streamflows are estimated to be lower than in the baseline, "no climate change" scenario (for the period 1986-2005).[108] By the late century period, however, economic impacts to bridge infrastructure are positive and total about $5 million annually for all of Delaware.

TABLE 5-5. ANNUAL ECONOMIC IMPACTS TO BRIDGES FROM CLIMATE CHANGE ($MILLION)

Economic impacts are defined as repair and delay costs above the baseline climate scenario (1986-2005) on bridges affected by scouring and deck overtopping from high river flow events. Impacts are measured in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	-$0.62	-$0.67	-$0.70	-$0.68	$1.2	$1.6
New Castle County	-$1.2	-$1.2	-$1.3	-$1.3	$2.3	$3.0
Sussex County	-$0.42	-$0.45	-$0.47	-$0.46	$0.84	$1.1
Delaware Total	**-$2.2**	**-$2.4**	**-$2.5**	**-$2.4**	**$4.4**	**$5.7**
Note: Negative values in this table represent reductions in damages relative to the modeled baseline period damages, owing to a reduction in the projected high streamflow events expected to cause damage to bridge piers and from overtopping.						

As shown in **Table 5-6**, economic impacts to railways are roughly two orders of magnitude smaller than projected impacts to roadways, reflecting both a smaller rail inventory and a lower likelihood that extreme temperature could cause significant damage to rail traffic in Delaware.

TABLE 5-6. ANNUAL ECONOMIC IMPACTS TO RAILWAYS FROM CLIMATE CHANGE ($MILLION)

Economic impacts are defined as repair and delay costs above the baseline climate scenario (1986-2005) on railways affected by extreme temperatures. Impacts are measured in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$0.015	$0.013	$0.022	$0.018	$0.049	$0.019
New Castle County	$0.14	$0.10	$0.32	$0.18	$0.79	$0.18
Sussex County	$0.025	$0.023	$0.033	$0.028	$0.068	$0.030
Delaware Total	**$0.18**	**$0.14**	**$0.37**	**$0.22**	**$0.91**	**$0.23**

Finally, as shown in **Table 5-7**, results for all three categories of infrastructure are largest in New Castle County but impacts to roadways are only slightly less or comparable for Sussex County.

---

[108] The streamflow modeling for bridges is specific to where potentially vulnerable bridges are located and does not necessarily reflect broader streamflow trends in Delaware.

TABLE 5-7. TOTAL ANNUAL ECONOMIC IMPACTS TO RAILWAYS, BRIDGES, AND RAILWAYS FROM CLIMATE CHANGE ($MILLION)

Economic impacts are defined as repair and delay costs above the baseline climate scenario (1986-2005) on roads, railways, and bridges. Impacts are measured in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$2.2	$2.6	$4.2	$3.6	$16	$7.7
New Castle County	$31	$21	$32	$20	$72	$50
Sussex County	$25	$23	$41	$33	$74	$36
Delaware Total	**$58**	**$47**	**$77**	**$57**	**$160**	**$94**

Limitations:

- Infrastructure inventory data for the U.S. EPA cited sources differs from that available from DelDOT sources. We therefore calibrated the results for road and rail categories to reflect recent DelDOT data on road and rail inventories. Road miles for the cited sources are about 40 percent higher than from DelDOT sources, a difference which may be attributed to the need to use relatively coarse, 25 km grid cell resolution data from the U.S. EPA national data. The DelDOT data is believed to be more accurate and current. The calibration may underestimate impacts for roads, however, if the DelDOT data exclude some tertiary or unpaved roads that could be subject to climate impacts. Rail miles in the U.S. EPA sources are found to be about 40 percent less than DelDOT data, possibly for the same reasons attributed to the relatively coarse resolution of the U.S. EPA data.
- Modeling of the reactive adaptation scenario assumes that transportation agencies respond quickly to climate change damage to road, rail, and bridge infrastructure. The amount of time required to respond in "reactive" mode varies by the severity of damage and is consistent with typical periods necessary for contracting and repair tasks. The typical times to repair do not consider the possibility that, with climate change, multiple repairs may be required simultaneously, statewide. Any additional delays in scheduling or completing repairs to infrastructure might increase the economic impact estimates.
- Nationally representative repair costs were used based on standard construction cost and time-to-complete estimates from standard construction cost sources. Delaware-specific costs to repair may be higher or lower.

5.2 HIGH AND SIGNIFICANT HAZARD DAMS

More frequent and intense precipitation events on "high hazard" and "significant hazard" dams that are owned and maintained by the state of Delaware

DNREC and DelDOT jointly administer a program for dam safety in Delaware to prevent dam failure. Dams in the program are classified in hazard categories from low to high based on their potential risk to life, health, and property, should the dams fail. The categorization does not account for the condition of these dams, or the likelihood of failure to occur. Climate change could lead to more frequent overtopping of some, or all of these dams, causing flooding of downstream areas, even if the dam safety program remains successful at avoiding complete dam failure.

Methods:

We analyze impacts to 39 high and significant hazard dams, as identified by DelDOT and Delaware Department of Natural Resources and Environmental Control (DNREC). Site-analyses for flood damage, which in many instances may have been conducted for Delaware dams, are not publicly available. It is not within the scope of this valuation exercise, however, to conduct a new flooding impact analysis for overtopped or failed Delaware dams as a result of high precipitation events. A typical site-specific analysis would involve detailed data collection, site characterization, and hydrologic and hydraulic modeling under varying potential precipitation and flood conditions. Instead, IEc interviewed dam program experts in DelDOT and DNREC for information on historic damages at Delaware dams during high-flow conditions, and to guide reasonable assumptions about the engineering standards that could apply to the set of dams analyzed here, to estimate the future likelihood of dam overtopping and breach events. IEc then used a downscaled version of the HUC level projected streamflow results of the Hydrologic and Water Quality System, as outlined in Fant et al. (2017) to simulated future hydrologic conditions at each dam site and assess the frequency of potential dam failure modes.[109]

Economic impacts representing flood damages to nearby buildings and infrastructure based on four elements of data for each dam site: (1) an average estimated area of influence for flooding associated with an overtopping event; (2) the average county level building value per acre in the area surrounding each dam in Delaware; (3) standard U.S. Army Corps of Engineers depth damage functions for Delaware that are used to estimate building damages associated with a certain freshwater flood height, and (4) estimates of the cost of dam repairs necessary after an overtopping or breach event.

Estimates of the cost of dam repairs necessary after an overtopping or breach event are developed based on DNREC and DelDOT report dam safety incidents, characteristics, and

---

[109] Charles Fant, Raghavan Srinivasan, Brent Boehlert, Lisa Rennels, Steven C. Chapra, Kenneth M. Strzepek, Joel Corona, Ashley Allen, and Jeremy Martinich. (2017). Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins. Water , 9:118-138), doi:10.3390/w9020118. The HUC-8 level results were used in this work. IEc also considered use of the Wobus et al. (2017) HUC level results, but the focus in that published work on the 100-yr flow proved too limiting for this particular application. See Wobus, Cameron, Ethan Gutmann, Russell Jones, Matthew Rissing, Naoki Mizukami, Mark Lorie, Hardee Mahoney, Andrew W. Wood, David Mills, and Jeremy Martinich. (2017). Climate change impacts on flood risk and asset damages within mapped 100-year floodplains of the contiguous United States. *Nat. Hazards Earth Syst. Sci.*, 17:2199-2211.

estimated economic damage to a national database.[110] Nine incidents in Delaware were reported to this database between 2011 and 2017, five of which were identified at high hazard dams, and one at a significant hazard dam. Seven of these incidents were associated with a single high precipitation event, Hurricane Irene in 2011 and almost all events were overtopping events. The national database records only ranges of damage, so we also spoke with DelDOT and DNREC representatives to develop more precise estimates of damage. The average economic damage is approximately $188,500 per event.

Second, to estimate potential area affected and depth of potential flooding, IEc researched available inundation flood modeling that estimates flood area and depth of inundation for Delaware dams or other potentially comparable dams in the hypothesized event of dam breach or failure. DNREC staff reviewed relevant modeling for Delaware dams not available to the public, and IEc reviewed two readily available Emergency Action Plans for dams in Massachusetts that include such analysis.[111] The results indicated that, in a breaching event, up to 36 structures might be affected by flooding, with depths of approximately 2.0 feet.

Based on the limited information available, we develop changes in the occurrence probability of two types of events: overtopping and breaching. We estimate that an overtopping event could result in $188,500 of damage, based on the average damage from the Dam Safety Incident Database for reported in-state events.[110] Breaching events are assumed to cause damage consistent with an average of 2.0 ft of standing water flood depth, based on consultation with DNREC staff. To estimate structural damage, we used standard depth-damage functions and structure value derived from the National Coastal Properties Model database of value for each of Delaware's three counties. We assume all non-structural damage to properties would be approximately equal to the damage to structures, consistent with the total damage from the readily available Emergency Action Plan.[111] Non-structural damage could include damage to roads or, other infrastructure; local response and cleanup costs beyond structure damage; business interruption; and traffic delays.

Based on discussions with DelDOT and DNREC staff, we assume that dams in Delaware were designed to the 100-year event (1-percent annual likelihood event) for overtopping and 500-year event (0.2-percent) for dam breaching. As these rare events are difficult to discern in the historical record, it is necessary to use a statistical technique to identify the flow associated with the return periods of interest. Using 20 years of historical flow data from Fant et al. (2017), we fit a Gumbel distribution (a unique form of the generalized extreme value distribution often used for extreme events of precipitation or river flow) to the available data. We then apply the same technique for the projected years and compare the projected distribution for each of the future eras to the historical distribution. By comparing the number of times the flow exceeds the overtopping or dam breaching threshold in the historical period with the same estimates for the future period, we obtain an estimate of the change in expected annual impacts for the future

---

[110] Association of Dam Safety Officials, Dam Safety Incident Database, https://damsafety.org/incidents , results are based on a search of the database for all reported incidents in Delaware.

[111] DNREC staff reviewed relevant flood modeling for several dams. IEc reviewed two publicly available Emergency Action plans, including EMERGENCY ACTION PLAN for Foster's Pond Dam; Andover, Essex County, Massachusetts; National I.D. Number: MA00153; State ID Number: 5-5-9-10; Dam Location: 42.61361° N / 71.14146° W; and EMERGENCY ACTION PLAN for Forge Pond Dam; East Bridgewater, Plymouth County, Massachusetts; National I.D. Number: MA00427; State ID Number: 7-12-83-3; Dam Location: 42.0368° N / 70.9595° W

period. For example, if a flow event in the historical period is a 1-percent flood event, and these same flows occur with 2-percent per year frequency in the future projection, annual expected damages for the future projection would be double the baseline annual expected damages.

The data sources used in this analysis are summarized in **Table 5-8**.

TABLE 5-8. HIGH AND SIGNIFICANT HAZARD DAMS ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Simulated daily river flow	Simulated daily river flows for 2,110 8-digit HUCs across the Contiguous United States, 7 of these in Delaware	Fant, Charles, Raghavan Srinivasan, Brent Boehlert, Lisa Rennels, Steven C. Chapra, Kenneth M. Strzepek, Joel Corona, Ashley Allen, and Jeremy Martinich. (2017). Climate Change Impacts on U.S. Water Quality Using Two Models: HAWQS and U.S. Basins. Water , 9:118-138), doi:10.3390/w9020118.
Damage per event	Approximate damage per event from two sources: DNREC/DelDOT and Massachusetts Emergency Action Plans	DNREC/DelDOT – Association of Dam Safety Officials, Dam Safety Incident Database.[110] Massachusetts Emergency Action Plan for Foster's Pond Dam; Andover, Essex County.[111]
Dam locations	Geo-located shape file of dams in Delaware, includes hazard classifications	DelDOT.
Building values	Average building value by county, used for the damage of dam breaching events	Neumann, J.E., Chinowsky, P.,, Helman, J., Black, M., Fant, C., Strzepek, K., and Jeremy Martinich. Submitted: Climate effects on U.S. infrastructure: the economics of adaptation for rail, roads, and coastal development. Submitted to Climatic Change.

Results:

Table 5-9 shows the annual estimated future impacts of climate change (difference from the baseline) from overtopping and breaching events for the four significant hazard dams and the 35 high hazard dams evaluated. While overtopping events are fixed at $188,500 per event, breaching events vary by location but average to slightly more than $2.5 million per event.

Impacts are generally predicted to increase over time for Delaware. Impacts for RCP8.5 are always higher than damages for RCP4.5, as expected. Near and mid-century impacts are negative (or a reduction in damages relative to the modeled baseline period damages) for New Castle County indicating that these extreme events are less likely to occur with climate change, compared to the baseline period, in New Castle County. Across Delaware, annual expected baseline period damages are $275,000.

TABLE 5-9. ANNUAL EXPECTED ECONOMIC IMPACTS FROM OVERTOPPING AND BREACHING OF SIGNIFICANT AND HIGH HAZARD DAMS DUE TO CLIMATE CHANGE

Economic impact are defined as flood impacts to structures as compared to impacts in the baseline climate scenario (1986-2005), measured in dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$139,000	$177,000	$123,000	$62,000	$378,000	$2,300
New Castle County	-$5,100	-$49,000	-$6,800	-$5,800	$40,000	$75,000
Sussex County	$212,000	$53,000	$142,000	$82,000	$734,000	$142,000
Delaware Total	**$345,000**	**$181,000**	**$258,000**	**$139,000**	**$1,153,000**	**$220,000**

Note: Negative values in this table represent reductions in damages relative to the modeled baseline period damages, owing to a reduction in the projected high streamflow events expected to overtop or breach dams. The annual expected baseline period damages are estimated at $275,000.

Limitations:

- Costs per event are based on the available information from consultation with DNREC and DelDOT staff, DNREC review of available dam-specific flood modeling, the incident database and Massachusetts Emergency Action Plans. Detailed, project-level estimations of flood damage that are unique to each dam would improve the estimate of cost but would require a significantly expanded level of effort.
- Streamflow simulated at the project-scale with bootstrapping (artificially generated flows) would improve the estimation of event occurrence for both the historical period and the future period, but would also require a significantly expanded level of effort. Estimating occurrence probabilities of 100- to 500-year events over 20 years of data, as we have done here, can result in less reliable solutions.
- Many of Delaware's dams are old, as a result information on the applicable engineering standards for overtopping and breach cannot be reliably determined. We ran a sensitivity analysis with the alternative assumption of a lower engineering standard of 50-year flow leading to an overtopping, and a 100-year flow leading to a breach. The result showed both baseline damages and damages attributable to climate change increasing by a factor of 3 or more. Based on historical damages and rates of overtopping and breaching, however, we believe the primary assumption of 100-year flow leading to overtopping and 500-year flow leading to breach are likely to be more accurate for Delaware's dams, in part because several overtopping and 100-year flow events have occurred historically in Delaware, but no breach events has yet been documented in incident reports.

5.3 CULVERT DAMAGE AND ROAD CLOSURES FROM FLOODING

High precipitation and extreme weather events, which may be more frequent in the future, could increase the chance of culvert failure causing damage to the culvert and road, as well as road closures

Culverts, which allow flows to pass under roadways and are designed to prevent overtopping or road washout during flood events, are vulnerable to changes in the frequency and intensity of floods. These events may change significantly over this century due to climate change, with events larger than the floods these culverts were designed to withstand.

Methods:

We analyzed impacts to 904 culverts that are included in the Delaware bridges database.[112] This number includes only those culverts over streams and rivers or other waterways that have the potential to flood.[113] These culverts include necessary details like location and can be linked with roadway information (e.g., number of lanes, traffic statistics). Our approach to analyzing these culverts includes three parts:

1. Establish a total failure damage estimate for each culvert, which includes approximate costs of culvert replacement to the same standard as originally built; road reconstruction; and indirect costs of traffic delays.
2. Determine three levels of culvert failure, triggered when flows exceed required design flows at three levels: quarter, half, and full damage.
3. Estimate changes in the occurrence of culvert failures across Delaware using extreme value statistics and daily simulated flows.[114]

The cost of total failure includes the three parts. We use an approximate culvert replacement cost based on an assessment of culvert repair and replacement projects:[115] average costs for major and minor roads are estimated to be roughly $35,000 and $10,000, respectively, adjusted for inflation to 2019 dollars. Major roads are defined as interstates, arterials, and collectors; minor roads are all other roads in the inventory. These estimates are the average cost of 314 projects. The per lane mile cost to rebuild the road after a washout was approximated from typical costs from the latest *Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Report.*[116] The result is a cost of $100,000 per lane per washout event, which includes the excavation and reconstruction of several hundred feet for the transition from the new structure to the undamaged portion of roadway.[117] Average labor hours for replacing a failed culvert are considerably larger for major roads (300 hours), than minor roads (closer to 50 hours).[115] Since repair for major roads will likely necessitate a larger construction crew than minor roads, we

---

[112] Provided by DelDOT

[113] Note that culvert bridges were excluded in the analysis of bridges in Chapter 5.1. Also, this is only a partial assessment Because we expect there could be many more culverts than these 904, for example, small culverts not tracked by DelDOT.

[114] Fant, Charles, Raghavan Srinivasan, Brent Boehlert, Lisa Rennels, Steven C. Chapra, Kenneth M. Strzepek, Joel Corona, Ashley Allen, and Jeremy Martinich. (2017). Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins. Water, 9:118-138), doi:10.3390/w9020118.

[115] 2015 Maintenance Culvert Cost Data Analysis, conducted by the Minnesota Department of Transportation, http://www.dot.state.mn.us/bridge/hydraulics/culvertcost/2015%20Drainage%20Maintenance%20Data%20Summary%20-%20Final%20Version.pdf

[116] Appendix A-1 of the biennial Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance (23rd Edition), a report the U.S. Department of Transportation prepares for Congress, 2019. https://www.fhwa.dot.gov/policy/23cpr/

[117] Estimate of surrounding road area affected during a washout provided by DelDOT

assume the road will be closed for two days for minor roads and three days for major roads. Average annual daily traffic for these roads were provided by DelDOT and joined at the culvert locations. Acknowledging that drivers are likely to find alternative routes to their destination, we use the rerouting factor used in Fant et al.[118] which is essentially a ratio of the sum of traffic of surrounding roads over total road capacity for all surrounding roads. These ratios are applied directly to the delays to reduce delays proportionally, as was the approach in Fant et al. Hours of delay are the product of the total construction time, in days, and the average annual daily traffic, adjusted by the factor to account for alternative routes. The valuation of hourly delay is consistent with that used in Chapter 5.1 for road delays.[119]

According to the DelDOT Road Design Manual,[120] culverts are designed to the 50-year (or 2-percent) flood event for major roads and to the 25-year (or 4-percent) flood event for minor roads. If streamflows exceed design flows, damage occurs based on categorical threshold levels. Damages will fall into three distinct categories: 25 percent damage, 50 percent damage, and total failure. Major roads reach the 25 percent damage threshold when a 100-year (1-percent) event occurs, 50 percent damage threshold when a 200-year (0.5-percent) event occurs and total failure for a 400-year (0.25-percent) event. Similarly, local roads reach the 25 percent damage threshold for a 50-year (2-percent) flood event, 50 percent damage threshold for a 100-year (1-percent) event and total failure for a 200-year (0.5-percent) event. Total failure estimates based on the assumptions for costs and damage thresholds are shown in Table 5-10, with other assumptions described in this section. Costs for 25 percent and 50 percent damaged culverts are estimated proportionately to the total failure value.

TABLE 5-10. CULVERT COST AND DAMAGE ASSUMPTIONS

ASSUMPTION	MINOR / LOCAL ROADS	MAJOR ROADS
Culvert replacement cost[115]	$10,000 per event	$35,000 per event
Road repair / replacement[116]	$4,000 per lane (rural), $8,000 per lane (urban)	
Road closure duration[115]	2 days	3 days
Design flood event[120]	4-percent (25-year) flood	2-percent (50-year) flood
25 percent damage	2-percent (50-year) flood	1-percent (100-year) flood
50 percent damage	1-percent (100-year) flood	0.5-percent (200-year) flood
Total failure	0.5-percent (200-year) flood	0.25-percent (400-year) flood

Estimating the changes in frequency of flood events for the baseline and future eras follows the same approach used for high and significant dams as described in Chapter 5.2. Summarizing the approach briefly, we use extreme value statistics to estimate the streamflows in the historical period that correspond to the design flood events indicated in **Table 5-10** above. We then examine the streamflow projections for future eras to identify the frequency of occurrence of damage or total failure.

---

[118] Fant, Charles, Jennifer M. Jacobs, Paul Chinowsky, William Sweet, Natalie Weiss, Jo E. Sias, Jeremy Martinich, and James E. Neumann. Submitted: Mere nuisance or growing threat? The physical and economic impact of high tide flooding on US road networks. Submitted to Journal of Infrastructure Systems.

[119] U.S. DOT. 2016b. Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. Downloaded from https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf

[120] DelDOT Road Design Manual, available at https://deldot.gov/Publications/manuals/road_design/index.shtml

The data sources used in this analysis are summarized in **Table 5-11**.

TABLE 5-11. CULVERT DAMAGE AND ROAD CLOSURES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Culvert attributes	Database of bridges with location, purpose, feature under road (e.g., name of river or pathway), characteristics of the road above, etc.	DelDOT.
Traffic counts	Geolocated roads in Delaware with recently recorded traffic counts	DelDOT.
Simulated daily river flow	Simulated daily river flows for 2,110 8-digit HUCs across the Contiguous United States, 7 of these in Delaware	Fant, C., Srinivasan, R., Boehlert, B., Rennels, L., Chapra, S.C., Strzepek, K.M., Corona, J., Allen, A. and Martinich, J. 2017. Climate Change Impacts on U.S. Water Quality Using Two Models: HAWQS and U.S. Basins. Water. 9, 118-138.
Culvert replacement cost	Average repair and maintenance costs and labor hours for culvert replacement for over 300 projects in Minnesota	Maintenance Culvert Cost Data Analysis. 2015. Minnesota Department of Transportation. http://www.dot.state.mn.us/bridge/hydraulics/culvertcost/2015%20Drainage%20Maintenance%20Data%20Summary%20-%20Final%20Version.pdf
Road repair / replacement cost	Typical costs of rebuilding a road	Biennial Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance (23rd Edition), a report the U.S. Department of Transportation prepares for Congress. 2019. Appendix A-1. https://www.fhwa.dot.gov/policy/23cpr/
Economic cost of traffic delays	Different sources were used for passenger and freight vehicles. For passenger vehicles, the approach follows that recommended in U.S. Department of Transportation (2016) For freight vehicle travel, we rely on data from the National Cooperative Highway Research Program that are used as inputs to their Truck Freight Reliability Valuation Model (2016)	Passenger vehicles: U.S. Department of Transportation. 2016. Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf Freight vehicles: National Cooperative Highway Research Program. 2016. Report 824: Methodology for Estimating the Value of Travel Time Reliability for Truck Freight System Users. http://www.trb.org/Publications/Blurbs/174297.aspx

Results:

Average costs for culvert failure are projected to be about $250,000 for minor roads and about $740,000 for major roads. Indirect delay costs account for 14 percent and 49 percent of the total costs for minor and major roads, respectively. Of course, these delay costs are incurred by the user while the repair and rebuilding costs would be incurred directly by road maintenance agencies such as local or state departments of transportation. However, for the sake of our analysis, these costs are bundled into a single cost calculation.

Table 5-12 shows the annual expected impacts of climate change (difference from the baseline) from culvert damages by county, era, and RCP. Total damages for the state are higher for RCP8.5 than RCP4.5, as expected. Economic impact is slightly negative (or a reduction in damages relative to the modeled baseline period damages) in the mid-century period for New Castle County under RCP4.5 and RCP8.5. This is consistent with a small decline in the specific type of high streamflow events that cause damage to culverts, but the negative economic impact is limited to that county, and only in that era. In all other cases, the economic impact of climate change is positive (or an increased cost). Impacts are projected to be higher in the near century than the mid-century, which has the lowest impacts. By the late century, impacts are highest. Further, in the late century the economic impact is highest for the middle level of damage (50 percent damage threshold).

TABLE 5-12. ANNUAL ECONOMIC IMPACT FROM CULVERT FAILURES DUE TO CLIMATE CHANGE ($MILLIONS)

Economic impacts are defined as annual economic impact as compared to the baseline climate scenario (1986-2005), measured in millions of dollars (2019) per year and averaged over 5 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$2.3	$0.67	$1.6	$0.85	$5.6	-$0.087
New Castle County	-$0.37	$1.0	-$1.7	-$1.6	$8.2	$12
Sussex County	$3.7	$1.5	$2.2	$1.1	$12	$4.0
Delaware Total	**$5.7**	**$3.2**	**$2.0**	**$0.30**	**$25**	**$16**

Note: Negative values in this table represent reductions in damages relative to the modeled baseline period damages, owing to a reduction in the projected high streamflow events expected to damage culverts.

Limitations:

- Costs are based on national data, adjusted to Delaware specific information where possible. The results will likely differ depending on site-specific details and the nature of the flood events which we are unable to capture in this analysis.
- The projections from climate models are considered unreliable for temporal scales below the daily scale (24-hr) precipitation event. Nonetheless, hourly or sub-daily precipitation events have occurred in the historical record and affected culverts in the state. This analysis unfortunately does not capture the effects of those sub-daily events, and so may underestimate the overall impact of climate change on culverts.
- Each road and culvert have site-specific details that will dictate the level at which damage occurs. The thresholds used here for levels of damage are approximated due to a lack of detail at each of these sites or reliable information on typical culvert failure events in relation to the flood event. Damaged or undersized culverts are likely to fail at lower thresholds than newer culverts built to updated current design standards.
- Streamflow simulated at the project-scale with bootstrapping (artificially generated flows) could improve the estimation of event occurrence for both the historical period and the future periods, but this type of analysis was not possible given the existing resource and time constraints.

5.4 ROAD CLOSURES FROM COASTAL FLOODING

Road closures due to high tide flooding, extreme weather events, and SLR, and road closures on local feeder roads in coastal communities due to high tide flooding, extreme weather events, and SLR

Coastal flooding poses a risk to traffic flow, causing periodic road closures. As sea levels rise, these flood events will be more frequent and persist for a longer period. High tide flooding episodes (sometimes referred to as "minor," "nuisance," or "sunny day" flooding) were overlooked in the past because these events do not typically cause significant infrastructure damage.[121] However, high tide flood events can be more costly than extreme events over time to low-lying infrastructure like roadways because they occur more frequently. Recent work on high tide flooding and its effects on the road system (Fant et al. submitted),[122] combined with the most recent applications of the National Coastal Property Model (Neumann et al. submitted)[123] for SLR and storm surge, provide the framework needed to estimate road closures due to all three of these coastal hazards for all of Delaware's road systems.

Methods:

We followed a similar analytical approach for both high tide flood events and less frequent but more severe storm surge events. This approach is outlined in the five steps below (described in detail in Fant et al.):

1. The tide gauge water level is determined using hourly records from NOAA tide gauges over a 19-year period from 1999 to 2017. Long-term trends are removed from the data and the result is centered on the year 2000, which is the baseline of the SLR projections. The distributions of hourly tide levels provide a means to identify when the highest tides in any year may lead to high tide flooding of roads.
2. The road network is segmented by intersections and ramps, and traffic data are assigned to each segment as intersections provide on and off points along the road.
3. The datasets from #1 and #2 are overlain on a floodplain map to identify vulnerable roads and, from the hourly tide distribution, the flood duration for high tide flood events. The key results metric is vehicle-hours of delay, calculated as the product of flood duration and average annual hourly traffic. **Figure 5-2** provides a map that shows the components of the road network that are vulnerable to flooding at various water level heights, providing an overall sense of the degree to which roads could be affected. The inset provides additional detail for the Wilmington area, which at the larger map's scale is not visible.

---

[121] Some research is beginning to emerge to assess the long-term impacts of flooding on road pavement integrity and longevity, see for example: Mohamed Elshaer, Majid Ghayoomi & Jo Sias Daniel (2019) Impact of subsurface water on structural performance of inundated flexible pavements, International Journal of Pavement Engineering, 20:8, 947-957, DOI: 10.1080/10298436.2017.1366767

[122] Fant, Charles, Jennifer M. Jacobs, Paul Chinowsky, William Sweet, Natalie Weiss, Jo E. Sias, Jeremy Martinich, and James E. Neumann. Submitted: Mere nuisance or growing threat? The physical and economic impact of high tide flooding on US road networks. Submitted to Journal of Infrastructure Systems.

[123] Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Jeremy Martinich. Submitted: Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Submitted to Climatic Change; and Lorie, M., Neumann, J.E., Marcus C. Sarofim, Russell Jones, Radley M. Horton, Robert E. Kopp, Charles Fant, Cameron Wobus, Jeremy Martinich, Megan O'Grady, and Lauren E. Gentile, 2020: Modeling coastal flood risk and adaptation response under future climate conditions. Climate Risk Management 29(2020) 100233.

4. Impacts from storm surge events are addressed as a separate category of impacts, associated with the possibility that a specific storm surge event, such as a 1-percent storm, may occur in a future year. The method overall is identical to that for high tide flooding, except that instead of a time-bound high tide flood event that occurs with known frequency, we use the surge height associated with specific storm surge events to estimate inundated areas, and overlay that floodplain on the road network. These events do not have a duration specified, so in the absence of data we assume roads are inundated for 24 hours by any storm surge event. Note that we do not estimate the future probability of storm surge events; the 1-percent storm corresponds to the current 100-year storm intensity, rather than the future probability of such a storm, which could be higher or lower. In addition, this analysis does not consider floods from extreme precipitation or high riverine flow.
5. The economic impact of the vehicle-hours of delay metric is then valued using hourly rates for passenger and freight truck traffic delays, using the same valuation estimates for lost passenger and freight time as used in Chapter 5.1. We use delay cost estimates from U.S. DOT (2016) for passenger and heavy vehicles,[124] road user cost analysis from DelDOT,[125] and operating and maintenance costs for freight vehicles from the National Cooperative Highway Research Program (2016).[126] The costs of direct damage to the road surface are not included in this analysis.

---

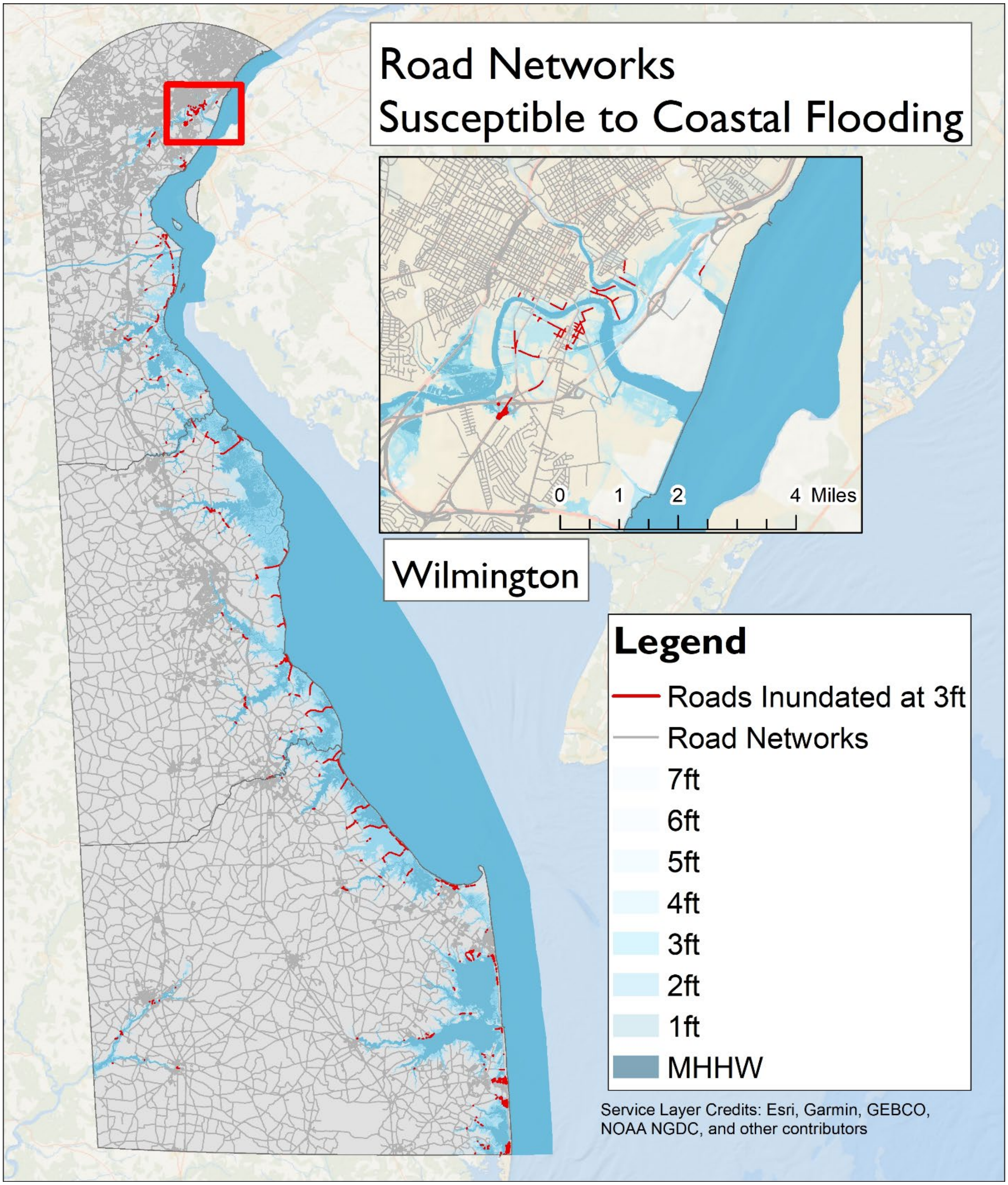
[124] U.S. DOT. 2016. Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. Downloaded from https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf

[125] Delaware Department of Transportation, Design Guidance Memorandum, 1-24 2019 Attachment Accessed Nov 2020 https://deldot.gov/Publications/manuals/dgm/index.shtml

[126] Freight vehicles: Methodology for Estimating the Value of Travel Time Reliability for Truck Freight System Users, document available along with Excel-based Truck Freight Reliability Valuation Model and User's Guide at: http://www.trb.org/Publications/Blurbs/174297.aspx

FIGURE 5-2. MAP OF ROAD NETWORKS SUSCEPTIBLE TO INUNDATION

Red lines show road segments inundated at 3 ft, which is roughly the high tide flooding level by mid-century.



Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

The delays from high tide flooding and storm surge events are associated with different climate stressors than those analyzed in Chapters 5.1 and 5.3 (such as extreme heat or high precipitation events), and so should be considered additive to delays estimated in those analyses. In this analysis, roads vulnerable to high tide flooding and storm surge flooding are identified for each 1 ft increment in elevation using the inundation maps for 1-7 ft to align the estimates with DNREC's SLR projections. Delays and user costs are determined at each of these 1ft increments and interpolated to the heights for each era and flood type.

We use the road network provided by the Highway Performance Monitoring System,[127] which was also used in Fant et al. This road network uses seven Functional Classes to categorize road types. These are (1) Interstates, (2) Other Freeways & Expressways, (3) Other Principal Arterials, (4) Minor Arterials, (5) Major Collector, (6) Minor Collector, and (7) Local Roads. Functional Classes 1 and 2 often have on/off ramps, which are not included in the analysis because they may be elevated, and Digital Elevation Models may not be reliable for elevated roads. Bridges are also removed from the analysis for the same reason.

It is reasonable to expect that changes in population and economic activity, over time, could affect traffic volumes. To account for these changes, we apply population and economic projections to the baseline Average Annual Daily Traffic estimates, assuming that the number of passenger vehicles grows linearly with changes in population; the number of heavy vehicles, which primarily transport goods, grows linearly with projections in Gross Domestic Product (GDP). As referenced in Chapter 2.1, this analysis uses population projections at the county level from the Integrated Climate and Land Use Scenarios version 2. GDP projections are based on a combination of data from the 2016 Annual Energy Outlook[128] and a run of the Emissions Prediction and Policy Analysis version 6 model.[129]

Drivers are not likely to simply wait for the floods to recede but will often attempt to find alternate routes around the affected road segment. We adjust for this rerouting with a rerouting factor, which is a ratio of the sum of traffic of surrounding roads over the total road capacity for all surrounding roads. This calculation is done for each road, using a radius of 5 miles, which is about half the average trip length in the U.S. (Fant et al. provide further details on this approach). These ratios are applied to reduce delays proportionally, as in Fant et al. We also acknowledge that actions to protect property, such as constructing sea walls, will also protect roads. The National Coastal Properties Model estimates where and when sea walls are likely to be built using a least-cost decision tree. We use the results from this model to determine which roads are likely to be protected from this ancillary protection. Fant et al. find that vehicle re-routing to avoid delays and ancillary protection of roads from sea walls intended to protect property, together termed "Reasonably Anticipated Adaptation", reduce delays and costs by about five times.

---

[127] HPMS (2016). Highway Performance Monitoring System Field Manual. U. S. Department of Transportation, Office of Highway Policy Information, Office of Management & Budget (OMB) Control No. 2125-0028

[128] U.S. Energy Information Administration, 2016: Annual Energy Outlook. Note that we do not forecast any changes in the road network, because such a forecast would be largely speculative - our method only quantifies changes to traffic volume on the existing road network.

[129] Chen, Y.-H. H., S. Paltsev, J. Reilly, J. Morris, and M. Babiker, 2015: The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT Joint Program on the Science and Policy of Global Change, Report 278, Cambridge, MA. Available online at http://globalchange.mit.edu/research/publications/2892

The data sources used in this analysis are summarized in **Table 5-13**.

TABLE 5-13. COASTAL FLOODING ROAD CLOSURES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Road network and traffic data	Geolocated road lines with traffic data and other road characteristics	Highway Performance Monitoring System. 2016. Field Manual. U. S. Department of Transportation, Office of Highway Policy Information, Office of Management & Budget Control No. 2125-0028.
Tidal Water Levels	Hourly water levels from tide gauge stations were obtained from NOAA's Center for Operational Oceanographic Products and Services (NOS 2019) and methods for analysis are described in Sweet et al. (2018), 19-years of hourly water levels spanning from 1999 to 2017	Sweet, W., Dusek, G., Obeysekera, J. and Marra, J.J. 2018. Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086.
Economic cost of traffic delays	Values of Time are a per hour value of time lost in traffic delays. For this, we used DelDOT (2019) To quantify the operating and maintenance cost of delay for freight vehicles, we relied on data from the National Cooperative Highway Research Program that are used as inputs to their Truck Freight Reliability Valuation Model (2016)	Delaware Department of Transportation. 2019. Design Guidance Memorandum, 1-24 2019. https://deldot.gov/Publications/manuals/dgm/index.shtml Freight vehicles: National Cooperative Highway Research Program. 2016. Report 824: Methodology for Estimating the Value of Travel Time Reliability for Truck Freight System Users. http://www.trb.org/Publications/Blurbs/174297.aspx

Results:

Tables 5-14 and 5-15 show the projected total delay costs by county for the three eras and three coastal flooding events. Note that high tide flooding events are defined differently from the extreme events referenced elsewhere in this report. High tide flooding events are defined by the water level relative to the height of a road, meaning that tidal records inform both the frequency and duration of these events (see Step 1 of the description of the method provided above). As a result, we are able to estimate how many high tide flood events will occur, and for how long, for each change in water level associated with gradually rising seas. However, extreme events are defined by their severity level given the current climate — that is, the 10-percent and 1-percent severity storm under current climatic conditions. We do not estimate the future frequency of these extreme events. Rather, we estimate economic impacts of a storm surge event on the condition it will happen in a future year, on top of the water level that is forecast to occur in the future given the impacts of SLR. For this reason, high tide flood events increase in frequency and duration over time. By the end of the century, the cumulative effect of multiple high tide flood events in a given year can result in higher impacts than for an extreme event, which is modeled as if it were a one-time event in a future year. Note that, by the end of the century, due to SLR, some roads are expected to be affected by high tide flooding for the majority of the year.

TABLE 5-14. ANNUAL ECONOMIC IMPACTS FROM COASTAL ROAD FLOODING DUE TO SEA LEVEL RISE (HIGH TIDE FLOODING) ($MILLION)

Economic impacts are defined as delay costs above the no-SLR baseline (year 2000), measured in millions of dollars (2019) per year. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)	MID-CENTURY (2040-2059)	LATE CENTURY (2080-2099)
Kent County	$0.61	$3.1	$33.0
New Castle County	$1.7	$17	$450
Sussex County	$0.79	$4.6	$57
Delaware Total	**$3.1**	**$25**	**$540**

TABLE 5-15. ECONOMIC IMPACTS OF FROM COASTAL ROAD FLOODING DUE TO STORM SURGE ($MILLION)

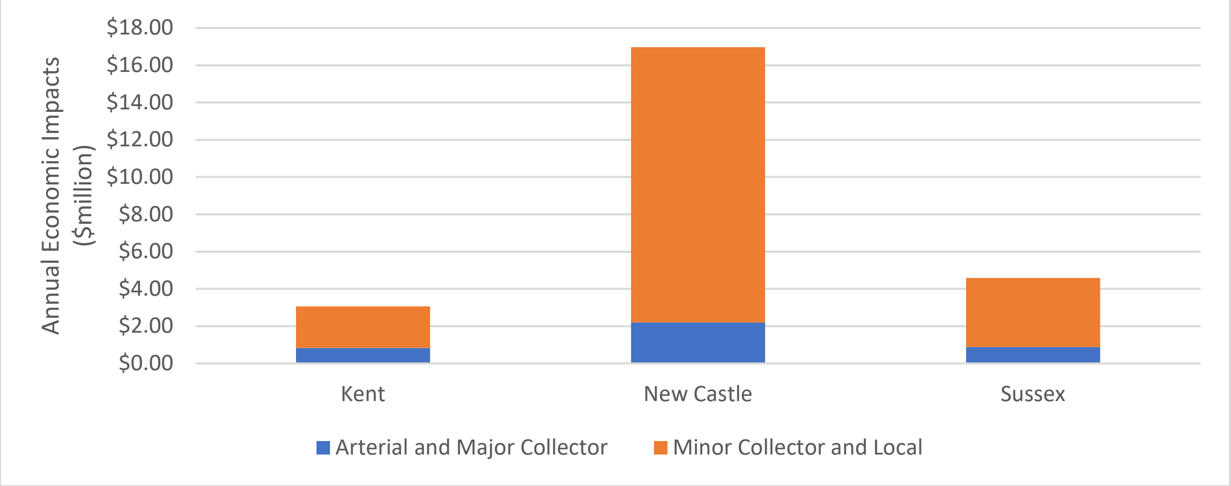
Economic impacts are defined as delay costs for the area inundated under a 10-percent and 1-percent storm surge event, measured in millions of dollars (2019) per year. The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions but take SLR into account over the course of the century. The values below represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year). Values may not sum due to rounding.

	Near Century (2020-2039)		Mid-Century (2040-2059)		Late Century (2080-2099)	
Storm Event	10% storm	1% storm	10% storm	1% storm	10% storm	1% storm
Kent County	$0.30	$0.49	$0.41	$0.59	$1.1	$1.3
New Castle County	$1.7	$7.2	$5.3	$15	$44	$55
Sussex County	$1.9	$10	$2.7	$8.9	$8.7	$15
Delaware Total	**$3.9**	**$18**	**$8.4**	**$24**	**$54**	**$71**

Our analysis does not find any closures for interstates, freeways, or expressways, designated as either Functional Classes 1 or 2 in the Highway Performance Monitoring System database. The majority of the costs in Kent and Sussex Counties are associated with closures of minor collectors and local roads for the state. However, arterials and major collectors in New Castle have higher associated costs in the mid-century and late century periods. **Figure 5-3** shows the costs associated with two road classification groups: arterial and major collector (Functional Classes 3-5) and minor collector and local (Functional Classes 6 and 7) for the mid-century.

FIGURE 5-3. ANNUAL ECONOMIC IMPACTS FOR ROAD CLOSURES FROM HIGH TIDE FLOODING FOR MID-CENTURY

Graphic shows annual delay costs for both arterial / major roads (functional classes 3-5) and minor / local roads (functional classes 6 and 7), above the no-SLR baseline (year 2000).



Limitations:

- Although we adjust traffic with both population and economic growth, traffic as well as road networks are constantly changing and are likely to be different from the traffic we use here.
- Road maintenance agencies may enforce permanent road closures or take other measures to encourage drivers to permanently find other routes for these roads, especially for roads that are flooded regularly by high tides (e.g., hundreds of times a year). In these cases, additional roads may be built, or other actions may be taken to account for road losses. Those adaptive action are not accounted for in this analysis.
- This analysis does not consider floods from extreme precipitation or high riverine flow. These events may at times coincide with tide-driven floods or storm surge events, causing additional delays.
- Some vehicles may be able to traverse shallow water with only minor speed reductions. We do not take that into account in this study. Fant et al.[122] finds that costs are sensitive to depth by about 0.9 percent per cm (or 2.3 percent per inch), meaning that if we assume vehicles will traverse one inch of standing water on the road without a speed reduction, our estimates of costs would be reduced by about 2.3 percent. We also do not consider damage to vehicles that are driven through high tide flood events – our assumption is that the vehicle damage would likely far exceed the economic costs of re-routing or even waiting for the high tide flooding to subside. We nonetheless acknowledge that some drivers may attempt to drive through high tide flood inundated roads, and in those cases we likely underestimate the economic impacts.
- This analysis does not consider roads that are only partially inundated (e.g., only one outer lane); this analysis considers only roads where the center line is under water.

CHAPTER 6 | AGRICULTURE IMPACTS (DDA)

The Delaware Department of Agriculture (DDA) promotes the viability of food, fiber, and agricultural industries in Delaware through the services they provide. Understanding the impacts of climate change on agriculture in the state can help DDA provide the appropriate guidance to farmers and other natural resource producers. Climate change is likely to affect agriculture in a number of ways, including:

1. **Saltwater intrusion on groundwater** sources used to irrigate current agricultural lands and inundation of coastal cropland.
2. **Crop growth** due to temperature, precipitation, relative humidity, wind speed, and solar radiation.
3. **Irrigation needs for crop production** due to rising temperatures that increase crop evapotranspiration, and potentially because of decreased rainfall during the growing season.
4. **Agricultural labor**, in terms of lost wages in agriculture sector, due to fewer hours worked on high heat days.
5. **Current and predicted invasive and nuisance species**, in relation to herbicide and pesticide usage.
6. **Milk production in dairy cows** due to higher temperatures.
7. **Poultry farm energy demands and infrastructure,** related to heating and cooling costs.

Agricultural impacts in this study are nearly all measured in terms of lost revenues: crop sales, dairy production, and wages for agricultural workers. The remaining categories are estimated using direct expenses: groundwater pumping costs (irrigation needs) and poultry farm heating and cooling costs. As shown in **Table 6-1**, by the end of the century, large differences emerge between RCP8.5 and RCP4.5 outcomes (RCP stands for representative concentration pathways, which capture different emissions scenarios; see Chapter 2.1 for further details). Crop growth, measured in crop sales, is projected to increase by $1.7 million per year under RCP4.5 by the end of century (i.e., a negative impact or a net benefit compared to the baseline) as moderate warming combined with increased CO_2 fertilization may improve yields; however, under RCP8.5, sales are projected to decrease by $26 million. **Figure 6-1** shows the distribution of impacts by county. Impacts are largest in Sussex County, the agricultural hub of the state.

TABLE 6-1. ANNUAL STATEWIDE ECONOMIC IMPACTS TO AGRICULTURE CATEGORIES ($MILLION)

Figures represent total statewide impacts by RCP (for categories impacted by changes in temperature and precipitation) or by era only (for categories impacted by SLR, excluding storm surge) in millions of dollars (2019). As this table presents annual impacts, storm surge impacts are not included, as such impacts are estimated on a per-event basis. For further information on each category, please see Chapters 6.1 through 6.7.

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
6.1	Saltwater Intrusion and Inundation on Cropland	$0.47		$1.0		$2.5	
6.2	Crop growth[a]	$10	$2.6	$6.3	-$1.0	$26	-$1.7
6.3	Irrigation needs for crop production	$0.83	$1.2	$1.1	$1.1	$2.0	$0.79
6.4	Agricultural labor	$0.22	$0.20	$0.55	$0.38	$1.8	$0.62
6.5	Current and predicted invasive and nuisance species[b]	-					
6.6	Milk production in dairy cows	$0.34	$0.32	$0.58	$0.48	$1.0	$0.61
6.7	Poultry farm energy demands and infrastructure	$0.43	$0.40	$0.55	$0.28	$2.3	$0.48

Notes:
a. Negative values in this table represent reductions in damages relative to the modeled baseline period damages.
b. Invasive and nuisance species are discussed qualitatively, due to limited availability of necessary data, in Chapter 6.5.

FIGURE 6-1. AGRICULTURE ECONOMIC IMPACTS BY COUNTY

Totals reported in millions of dollars (2019) represent temperature and precipitation-based impacts (RCP8.5 or RCP4.5) plus SLR impacts. This figure presents annual impact values, totals do not include storm surge impacts, as such impacts are estimated on a per-event basis.

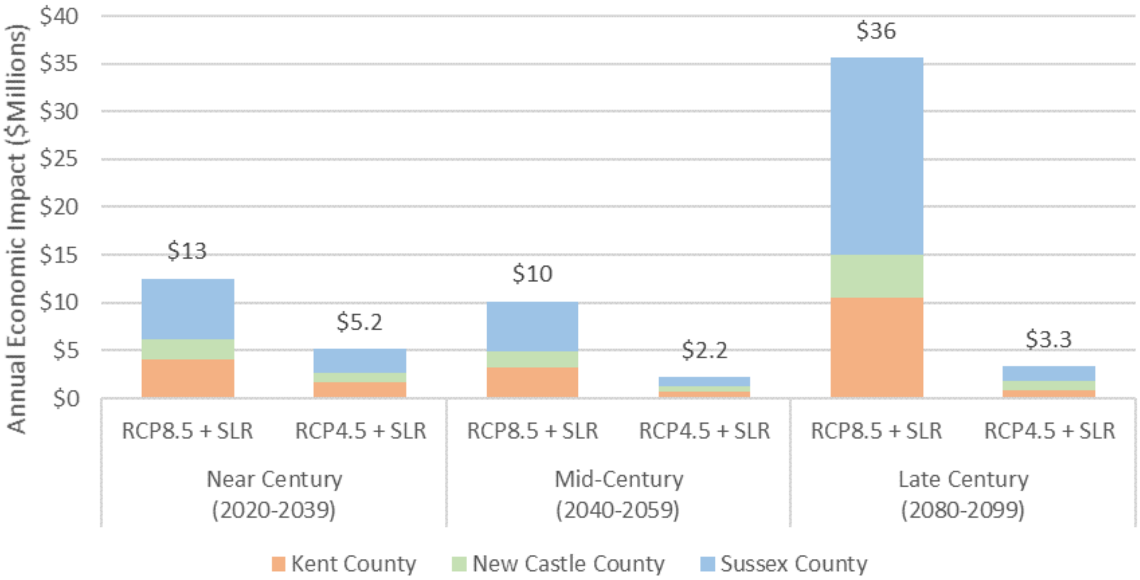


TABLE 6-2. STATEWIDE ECONOMIC IMPACTS TO AGRICULTURE CATEGORIES FROM STORM SURGE EVENTS ($MILLION)

Impacts shown below result from 1-percent and 10-percent storm surge events, reported in millions of dollars (2019). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The below values represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year).

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		10% Storm	1% Storm	10% Storm	1% Storm	10% Storm	1% Storm
6.1	Saltwater Intrusion and Inundation on Cropland	$2.3	$3.5	$3.7	$5.2	$5.8	$6.8

6.1 SALTWATER INTRUSION AND INUNDATION ON GROUNDWATER

Saltwater intrusion on groundwater sources used to irrigate current agricultural lands

SLR could potentially cause saltwater intrusion in some coastal aquifers, threatening groundwater-dependent irrigated agriculture reliant on those aquifers. In Delaware, 98 percent of irrigation is sourced from groundwater.[130] In addition, some coastal farms may be permanently lost due to SLR inundation or experience temporary losses due to salinization from storm surge flooding. In this analysis, we measure agricultural productivity losses from SLR inundation and storm surge (losses to both irrigated and non-irrigated areas) and saltwater intrusion (as conversion from irrigated to non-irrigated agriculture).

Methods:

Spatial data on farm area by crop is obtained from the U.S. Department of Agriculture CropScape database. We focus on areas attributed to the five main crops in Delaware (corn, soybeans, hay, wheat, and barley) including the area that is double cropped with barley/corn, barley/soybeans, and winter wheat/soybeans. We identify irrigated acres of farmland by overlaying the U.S. Geological Survey digital maps of center-pivot irrigated areas in the Mid-Atlantic region.[131] The total irrigated area included in the center-pivot irrigation is below the reported totals for the state based on the National Agricultural Statistics Service (NASS) Quick Stats database (113,933 acres in the U.S. Geological Survey dataset versus 154,948 in NASS Quick Stat), indicating the center-pivot irrigation dataset may not represent the full set of irrigated land. Therefore, we use the U.S. Geological Survey spatial data to identify the proportion of irrigated land inundated or infiltrated and apply those percentages to the NASS dataset. This is necessary because the economic impacts are measured as changes in sales value, as available from NASS by crop and county, therefore the adjustment allows our land area dataset to match our sales data. Crops sales were not available by irrigation status (i.e., non-irrigated or irrigated), therefore we estimate the crop sales by irrigation status for each crop using the proportion of land irrigated by crop and adjusting for the relative yields of non-irrigated versus irrigated crops as estimated for the baseline period in the Erosion Productivity Impact Calculator (EPIC for short, described further below).

To estimate the area of croplands lost to SLR we overlay this irrigation area spatial dataset with the 2017 Delaware Coastal Inundation layer. Following the process outlined in Chapter 2.2, we calculate the percentage of each crop by irrigation status and county expected to be inundated at each foot of SLR and translate the integer foot SLR scenarios into near century (0.75 ft), mid-century (1.5 ft) and late century (3 ft) results. The integer foot SLR data is also used to identify the inundated areas for the 1- and 10-percent storms in each era. This process produces an estimate of the percent of cropland inundated by SLR and storm surge by county, crop, and irrigation status, which is then applied to production values (at the same dimensions) to calculate total lost value.

---

[130] Delaware Geological Survey. Hydrologic Information for Delaware. [Online]. Available at https://www.dgs.udel.edu/water-resources.

[131] U.S. Geological Survey, University of Delaware Extension. 2019. Geospatial Compilation and Digital Map of Center-Pivot Irrigated Areas in the Mid-Atlantic Region, United States. [Online]. Available at https://firstmap.gis.delaware.gov/arcgis/rest/services/Hydrology/DE_Pivot_Irrigation/MapServer

Saltwater intrusion risk is a function of distance to the shore, topography, hydraulic conductivity, and pumping intensity, among other characteristics that are outside of the scope of the current analysis.[132] For a screening-level approach to estimating the potential for saltwater intrusion in groundwater aquifers used for irrigation, we define a buffer inland from the coastal inundation boundary, as defined by the Delaware Coastal Inundation layer, and assign a probability that irrigated cropland within the buffer experiences saltwater intrusion, and is therefore forced to switch to non-irrigated agriculture.[133] Jasechko et al. (2020) find that 44 percent of well water level observations within one kilometer (0.6 miles) and 20 percent of observations between nine and 10 kilometers (5.6-6.2 miles) of the coast are below sea level. Wells below sea level are particularly vulnerable to saltwater intrusion, however there are additional factors that would determine whether intrusion actually occurs.[134] In the absence of detailed modeling of the many factors influencing the likelihood of intrusion, we follow the findings of Jasechko et al. to estimate the economic impacts if 44 percent of irrigated land within one kilometer (0.62 miles) of the shore experienced intrusion, where the shore is defined as the boundary of the coastal inundation layer (i.e., identify irrigated area of within one kilometer of shore, by crop, and assume 44 percent of that land would be affected). The directional effect of this simplifying assumption is unknown; however, it is likely we overestimate the impact within the one kilometer buffer, as not all wells in the vulnerable area will experience intrusion. We do not estimate any effects beyond one kilometer, which is an offsetting underestimate. Yields from the irrigated areas experiencing saltwater intrusion are adjusted using crop-specific non-irrigated yield ratios for Delaware from the EPIC crop model to model the impact of conversion to non-irrigated agriculture, calculated as the average non-irrigated yield divided by the irrigated yield.[135] The resulting reduced yields are then used to calculate the change in production by crop and county. **Figure 6-2** shows an example of the output for 3 ft of SLR.

The data sources used in this analysis are summarized in **Table 6-3**.

---

[132] Klassen, J. and Allen, D.M., 2016. Risk of saltwater intrusion in coastal bedrock aquifers: Gulf islands, BC. Department of Earth Sciences, Simon Fraser University.

[133] Note there are alternative responses or preventative measures that could be taken before converting to rainfed agriculture. We assume those alternatives would be considered adaptation measures and did not consider them in this assessment. We also do not estimate impacts of storm surge on saltwater intrusion.

[134] Jasechko, S., Perrone, D., Seybold, H., Fan, Y., & Kirchner, J. W. (2020). Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. Nature communications, 11(1), 1-9.

[135] See Chapter 6.2 for more details on the EPIC model. Rainfed yield ratios for the baseline period are barley: 79%; corn: 73%; hay: 21%; soybeans: 71%; and wheat: 88%. Note that we hold rainfed ratios constant over time however there are expected to be slight changes as a results of other climatic factors. These changes are small (2.4% change on average across crops and eras) and are unlikely to significantly affect the results.

FIGURE 6-2. SEA LEVEL RISE INUNDATION AND INTRUSION BUFFER: 3FT SLR EXAMPLE

The map includes overlay of crop area, pivot irrigation schemes, SLR inundation at 3ft SLR (expected in late century), and 1km buffer beyond inundation boundary signifying the area susceptible to saltwater intrusion. Crop areas that are irrigated are identified by a red outline (often appearing as a circle for pivot irrigation schemes) around the crop type information. Inset shows agricultural region south of Slaughter Creek in Kent County, which exemplifies an area at risk of both SLR inundation and saltwater intrusion.

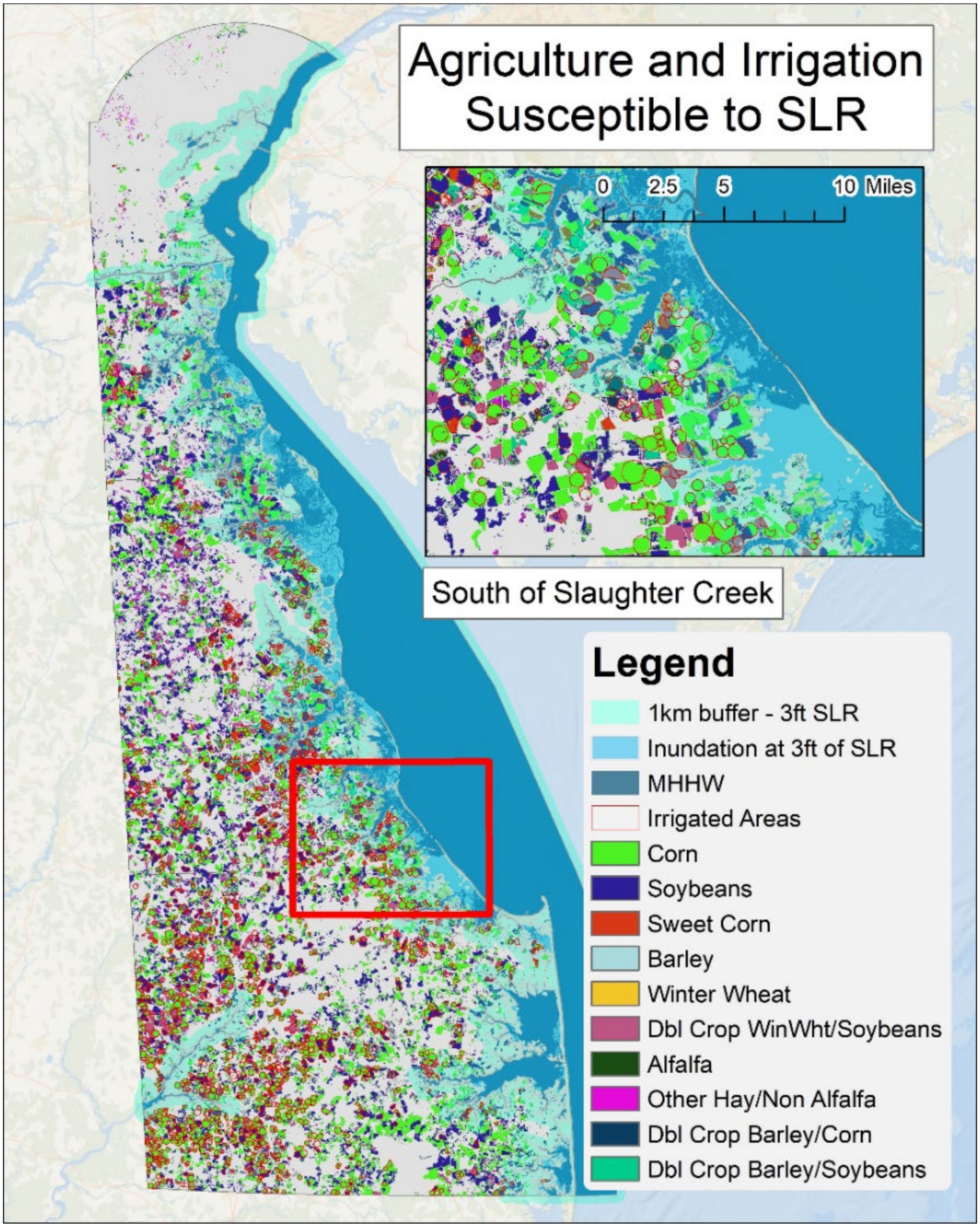


TABLE 6-3. SALTWATER INTRUSION AND INUNDATION ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Acreage by crop	GIS spatial dataset of land use, including agricultural uses by crop	U.S. Department of Agriculture. 2020. National Agricultural Statistics Service Cropland Data Layer. https://nassgeodata.gmu.edu/CropScape/
Pivot irrigation locations	GIS spatial dataset of pivot irrigation in the Mid-Atlantic region	U.S. Geological Survey, University of Delaware Extension. 2019. Geospatial Compilation and Digital Map of Center-Pivot Irrigated Areas in the Mid-Atlantic Region, United States. https://firstmap.gis.delaware.gov/arcgis/rest/services/Hydrology/DE_Pivot_Irrigation/MapServer
Crop yields	By crop, irrigation status, RCP, Global Circulation Model (GCM), and era; this analysis uses RCP and GCM averages by era (see Chapter 6.2 for more details)	EPIC model outputs developed for CIRA (2017) and based on Beach, R., Thomson, A., Zhang, X., Jones, R., McCarl, B., Crimmins, A., Martinich, J., Cole, J., Ohrel, S., DeAngelo, B., McFarland, J., Strzepek, K. and Boehlert, B. 2015. Climate change impacts on U.S. agriculture and forestry: benefits of global climate stabilization. Environmental Research Letters. 10(9).
Crop production values	Annual production, in terms of dollars, for 2007 to 2017	U.S. Department of Agriculture National Agricultural Statistics Service. 2017. NASS – Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats. Accessed 2020-12-04
Percent irrigated by crop	Source provided total irrigated and non-irrigated acres by crop and county	

Results:

Table 6-4 shows the predicted percent of each crop area that will be affected by each SLR stressor at each SLR elevation. Note that SLR is expected to reach 3 feet by late century but storm surge heights can reach over seven feet by end of century. Differences by crop are attributable to the spatial distribution of planting; for example, a higher proportion of corn is planted in areas vulnerable to SLR than barley.

TABLE 6-4. PERCENT OF CROPLAND AFFECTED BY INUNDATION AND INTRUSION

	SLR Elevation from Delaware Coastal Inundation Model						
	1ft	2ft	3ft	4ft	5ft	6ft	7ft
PERCENT CROPLAND (NON-IRRIGATED AND IRRIGATED) INUNDATED UNDER EACH SLR HEIGHT							
Barley	0.0%	0.0%	0.1%	0.3%	0.5%	0.8%	1.2%
Corn	0.2%	0.5%	1.0%	1.6%	2.3%	3.0%	3.8%
Hay	0.1%	0.3%	0.8%	1.2%	1.7%	2.2%	2.7%
Soybean	0.1%	0.4%	0.9%	1.4%	1.9%	2.6%	3.4%
Wheat	0.0%	0.1%	0.2%	0.4%	0.6%	0.9%	1.4%
PERCENT IRRIGATED CROPLAND EXPERIENCING SALTWATER INTRUSION AT EACH SLR HEIGHT*							
Barley	1.5%	2.4%	3.2%				
Corn	1.0%	1.4%	1.7%				
Hay	0.0%	0.0%	0.1%				
Soybean	1.0%	1.7%	2.1%				
Wheat	1.2%	2.2%	2.8%				
* SLR is expected to reach 3ft by late century. Intrusion is not modeled for storm surge. Based on 2020 cropland area and 2019 irrigation data.							

As shown in **Table 6-5**, statewide losses due to inundation and intrusion by the end of the century are estimated to reach $2.5 million annually, representing about one percent of current production of the five modeled crops. About $2 million of the impacts are related to inundation. The distribution of impacts across counties is more evenly distributed between Kent and Sussex Counties than might be expected given the larger share of agricultural activity in Sussex County. This appears to be the result of a higher proportion of farming activity concentrated near the coast in Kent County. Damages from inundation are 56 percent of total SLR impacts in near century but grow to 78 percent of damages by late century. As shown in **Table 6-6**, storm surge impacts are predicted to be significant, with the 10-percent storm increasing the SLR damages by about 300 percent on average across the century.

TABLE 6-5. ANNUAL ECONOMIC IMPACTS OF SEA LEVEL RISE INUNDATION AND SALTWATER INTRUSION DUE TO SEA LEVEL RISE ($MILLION)

Economic impact are defined as lost crop sales for five modeled crops due to SLR inundation and saltwater intrusion, relative to the no-SLR baseline (year 2000), 2020 cropland area baseline, and 2010 crop yield baseline, measured in millions of dollars (2019) per year. Crops include corn, soybeans, barley, hay, and wheat. Values may not sum due to rounding.

		NEAR CENTURY (2020-2039)	MID-CENTURY (2040-2059)	LATE CENTURY (2080-2099)
SLR Inundation	Kent County	$0.083	$0.22	$0.68
	New Castle County	$0.092	$0.22	$0.58
	Sussex County	$0.085	$0.23	$0.68
	Delaware Total	**$0.26**	**$0.66**	**$1.9**
Saltwater Intrusion	Kent County	$0.077	$0.11	$0.14
	New Castle County	$0.022	$0.049	$0.081
	Sussex County	$0.11	$0.19	$0.33
	Delaware Total	**$0.21**	**$0.35**	**$0.55**
Total	Kent County	$0.16	$0.33	$0.82
	New Castle County	$0.11	$0.27	$0.66
	Sussex County	$0.19	$0.42	$1.0
	Delaware Total	**$0.47**	**$1.0**	**$2.5**

TABLE 6-6. ECONOMIC IMPACTS OF STORM SURGE EVENTS FROM SALTWATER INUNDATION ($MILLION)

Economic impacts are defined as lost crop sales for the area inundated under a 10-percent and 1-percent storm surge event, measured in millions of dollars (2019) per year. The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The values below represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year). Values may not sum due to rounding.

	Near Century (2020-2039)		Mid-Century (2040-2059)		Late Century (2080-2099)	
Storm Event	10% storm	1% storm	10% storm	1% storm	10% storm	1% storm
Kent County	$0.75	$0.99	$1.3	$1.6	$2.2	$2.7
New Castle County	$0.52	$0.68	$0.81	$1.0	$1.2	$1.4
Sussex County	$1.0	$1.9	$1.6	$2.6	$2.5	$2.7
Delaware Total	**$2.3**	**$3.5**	**$3.7**	**$5.2**	**$5.8**	**$6.8**

Limitations:

- Saltwater intrusion risk is a function of many site-specific characteristics that could not be modeled in this analysis. The results above represent a screening assessment relying on simplifying assumptions.
- This analysis assumes land use remains constant over time, meaning no new farmland is developed as land area is lost to inundation and that farmers do not switch crops in response to changing conditions.
- We assume crop prices remain constant at baseline levels and hence do not adjust for future market changes, either related to, or independent of, climate change.
- Damages here are presented as a change from the baseline year and do not account for other changes in yield projected due to other climate change stressors, such as those presented in Chapter 6.2. For crops that are projected to see an increase in yields under future climates, this analysis underestimates the damages, while SLR impacts on crops with expected yield decreases may be overestimated.

6.2 CROP GROWTH

Crop growth due to temperature, precipitation, relative humidity, wind speed, and solar radiation

Crop growth is likely to be adversely affected by a changing climate, and particularly by extreme heat events and changing precipitation patterns. The impact does not affect all crops equally but can affect both irrigated and non-irrigated crops. We model the impacts of climate change on corn, soybean, hay, barley, and wheat yields and value the economic impact in terms of lost sales.

Methods:

The 2017 U.S. EPA's Climate Change Impacts and Risk Analysis report includes an agricultural yield and revenue analysis from which we extract yield impacts for Delaware. The Climate Change Impacts and Risk Analysis report followed the work of Beach et al. (2015) which uses the EPIC biophysical crop model to generate changes in crop yield, by agricultural region (including a 'Delaware' region), due to precipitation, relative humidity, wind speed, and solar radiation, with varied impacts by regional climate, soil type, irrigation status, and CO_2 levels.[136] We calculate the change in average yield compared to a 2010 baseline by crop and irrigation status for the near century, mid-century, and late century eras.

The data sources used in this analysis are summarized in **Table 6-7**.

TABLE 6-7. CROP GROWTH ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Projected yields	By crop, irrigation status, RCP, GCM, and year	EPIC model outputs developed for CIRA (2017) and based on Beach, R., Thomsom, A., Zhang, X., Jones, R., McCarl, B., Crimmins, A., Martinich, J., Cole, J., Ohrel, S., DeAngelo, B., McFarland, J., Strzepek, K. and Boehlert, B. 2015. Climate change impacts on U.S. agriculture and forestry: benefits of global climate stabilization. Environmental Research Letters. 10(9).
Crop sales values	Annual sales, in terms of dollars, for 2007 to 2017	U.S. Department of Agriculture National Agricultural Statistics Service. 2017. NASS – Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats
Percent irrigated by crop	Source provided total irrigated and non-irrigated acres by crop and county	

The EPIC model produce annual average yields for every fifth year between 1980 and 2099. by crop and irrigation status. The study includes five of the primary crops in Delaware (corn, soybeans, hay, barley, and wheat), on which we focus in this analysis. The EPIC model is a farm scale model that simulates potential production in areas within 100 kilometers of historical production regions to allow for shifts in production regions over time. Although results are reported as annual average changes in yields, the EPIC crop model has a daily temporal resolution, and thus implicitly incorporates extreme heat events, heat waves, and extreme precipitation events. EPIC does not include the effects of pests, disease, and ozone, or damage

---

[136] Beach, R., Y. C, A. Thomsom, X. Zhang, R. Jones, B. McCarl, A. Crimmins, J. Martinich, J. Cole, S. Ohrel, B. DeAngelo, J. McFarland, K. Strzepek, and B. Boehlert. 2015. Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. Environmental Research Letters. doi:10.1088/1748-9326/10/9/095004.

due to changes in the occurrence of storms, such as flooding, tornadoes, and hurricanes. Some of these effects are partially accounted for in other sections of this report (see Chapters 6.1 and 6.5); however, there are additional adverse impacts that are not captured in this analysis. EPIC assumes irrigation water is available as needed, therefore the impacts of water supply stress are not accounted for in this analysis (i.e., the impacts described in Chapter 3.1 would be in addition to the impacts described in this section). For more information on the EPIC model, please refer to Beach et al. (2015).

The calculated percent changes in yield from EPIC are then combined with annual sales totals to project future economic impacts. Sales values by crop are available from the U.S. Department of Agriculture NASS.[137] As production values are not available separately for irrigated and non-irrigated crops, we first develop average yield impacts by crop based on the relative area of irrigated and non-irrigated land by crop (also from NASS). Once calculated, these are applied to determine the total sales by county. Sales for non-irrigated and irrigated crops and percent of land irrigated by county and crop are shown in **Table 6-8.**

TABLE 6-8. BASELINE SALES ($MILLION) AND PERCENT IRRIGATED AREAS BY CROP AND DELAWARE COUNTY

Annual total sales (non-irrigated and irrigated) and irrigated areas from NASS (2020), averaged over available years 2007 to 2017.

	CORN	SOYBEANS	WHEAT	HAY	BARLEY
PRODUCTION VALUE (NON-IRRIGATED AND IRRIGATED)					
Kent	$33.4	$26.5	$11.1	$2.9	$2.1
New Castle	$13.5	$10.3	$4.2	$2.6	$0.3
Sussex	$80.5	$36.1	$12.0	$2.3	$3.1
Delaware Total	**$127.3**	**$72.9**	**$27.4**	**$7.7**	**$5.4**
PERCENT IRRIGATED					
Kent	39%	25%	32%	8%	15%
New Castle	12%	11%	12%	0%	0%
Sussex	55%	40%	39%	14%	20%
Delaware Total	**46%**	**30%**	**33%**	**7%**	**16%**

Results:

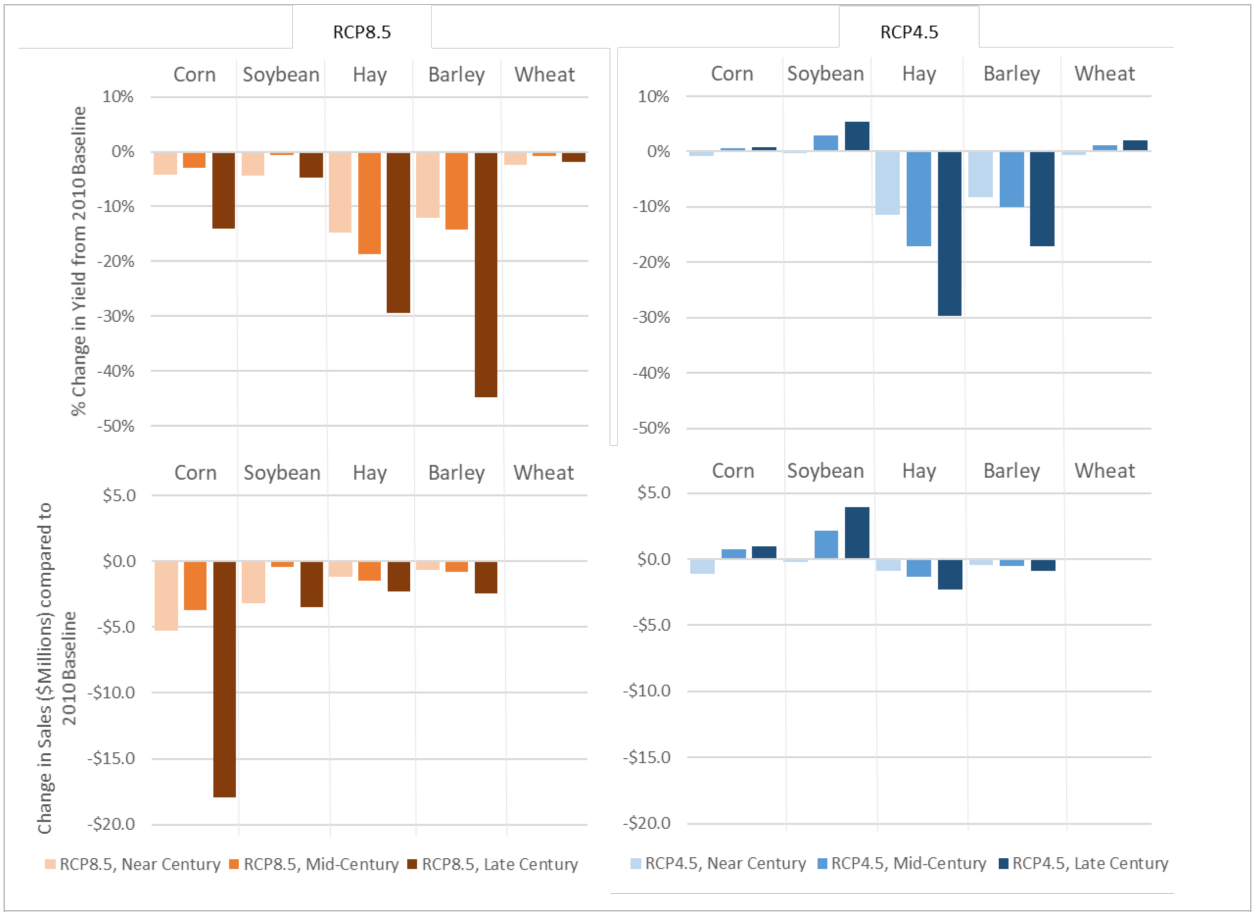
Yield impacts are projected to vary by crop and irrigation status, as shown in **Figure 6-3**. Corn, which is the primary irrigated crop in Delaware, is expected to have yield losses of about 14 percent by the late century under RCP8.5 but shows a slight increase in yields (0.8 percent) by late century under RCP4.5, as moderate warming combined increased CO_2 fertilization may improve yields. Soybean and wheat yield impacts follow a similar pattern. Hay and barley yields are projected to decrease in all future eras and mitigation scenarios, with losses as high as 45 percent (late century barley yields, RCP8.5).

---

[137] U.S. Department of Agriculture National Agricultural Statistics Service. (2017). NASS - Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats. Accessed 2020-12-04

FIGURE 6-3. CHANGES IN CROP YIELD AND SALES DUE TO CLIMATE CHANGE

Changes in yield presented as percent changes from 2010 crop yield levels, as modeled in EPIC for the Delaware region. Changes in sales calculated as change in yield multiplied by baseline sales by crop (2007-2017). Results shown for three eras and two emissions scenarios, averaged over 5 GCMs.



Note that while this report generally presents adverse impacts as positive values, in this graphic, negative changes in yield and sales represent reductions from the baseline.

As noted in **Table 6-8**, the yield changes in corn and soybean drive the economic results seen in **Table 6-9** due to the relative magnitude of production and price of each crop in Delaware. This is particularly evident under RCP4.5 where the relatively small improvements in yields for corn and soybeans outweigh the larger negative yield impacts (but lower overall production) of hay and barley, resulting in net increases in production value. The distribution of impacts across counties is generally proportional to total baseline production across regions, with over half of all damages occurring in Sussex County. Across the state, production changes in the late century are expected to range from an 11 percent decrease in value under RCP8.5 to a one percent increase in value under RCP4.5.

TABLE 6-9. ANNUAL ECONOMIC IMPACTS TO CROP SALES FROM CLIMATE CHANGE ($MILLION)

Economic impacts are defined as crop sales losses (corn, soybean, hay, barley, and wheat sales) relative to a 2010 crop yield baseline, measured in millions of dollars (2019) per year and averaged over 5 GCMs. Negative values represent increases in value as compared to the baseline. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$3.4	$0.90	$2.0	-$0.4	$7.4	-$0.68
New Castle County	$1.7	$0.56	$1.1	$0.016	$2.9	-$0.10
Sussex County	$5.2	$1.2	$3.3	-$0.7	$16	-$0.9
Delaware Total	**$10**	**$2.6**	**$6.3**	**-$1.0**	**$26**	**-$1.7**
Note: Negative values in this table represent reductions in damages relative to the modeled baseline period damages, owing to a shift towards climate conditions more suitable for growing certain crops.						

Limitations:

- This analysis assumes farmers continue to devote a constant amount of land to each crop over the analysis period and that farmers do not add irrigation systems. Crop switching and/or additional irrigation are potential adaptation measure not assessed here but could represent longer-term adaptation actions.
- We do not account for crop price changes that may result in changing supply or demand over time, both within Delaware and in the larger regional and national agricultural markets.
- This analysis does not account for the potential economic losses or gains in other crops not modeled.

6.3 IRRIGATION NEEDS FOR CROP PRODUCTION

Irrigation needs for crop production due to prolonged droughts, warmer average temperatures, and prolonged heat waves

Irrigation water requirements are likely to increase under climate change, both because of increasing temperatures that drive up crop evapotranspiration and potentially because of decreased rainfall during the growing season.

Methods:

We estimate the irrigation needs for corn, soybean, wheat, barley, and hay. To estimate crop water requirements during water shortages, we used the equations provided in the Food and Agriculture Organization of the United Nations, Drainage Paper No. 56 (Allen et al. 1998).[138] In this approach, crop water requirements are based on the phenology for each crop and estimates of potential evapotranspiration under baseline and climate change conditions. Since the majority of irrigation in Delaware is supplied by groundwater wells, we estimate the additional energy costs required to maintain irrigated yields at the baseline level. Energy costs for pumping increases linearly with the volume of water pumped, assuming the pumping depth stays constant.[139] Using average per acre energy costs for irrigation pumping in Delaware,[140] we estimate the costs required to pump the additional water compared to the baseline costs. Note that this category of damages addresses the same impacts described in Chapter 3.1, inadequate water supply for irrigation. In the previous section (Chapter 6.2), we assume no additional pumping occurs and therefore the losses are seen as yield impacts. Here, we assume farmers continue to provide adequate water to keep yields stable but incur additional pumping costs. These are two reasonable approaches to the same issue but serve as alternative estimates of the same damage and should not be summed.

The data sources used in this analysis are summarized in **Table 6-10**.

TABLE 6-10. IRRIGATION NEEDS ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Operating costs for irrigation pumps	Electricity costs paid for well pumps used for irrigation in Delaware in 2018.	United States Department of Agriculture, National Agricultural Statistics Service. 2018. Irrigation and Water Management Survey, Table 13 https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/index.php
Irrigated acres by crop	Total irrigated and non-irrigated acres by crop and county.	U.S. Department of Agriculture National Agricultural Statistics Service. 2017. NASS - Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats

---

[138] Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. FAO Irrigation and Drainage Paper No. 56. Rome: Food and Agriculture Organization of the United Nations, 1998.

[139] See equations employed in the California Air Resources Board Greenhouse Gas Emission Reduction Calculator Tool. 2016. California Department of Food and Agriculture (CDFA) State Water Energy Efficiency Program (SWEEP), https://www.cdfa.ca.gov/oefi/sweep/docs/GHG_CalculatorTool.xlsx. Last accessed: 2020-02-18.

[140] $22.30 per acre for wells, based on the 2018 Irrigation and Water Management Survey, Table 13, United States Department of Agriculture, National Agricultural Statistics Service, https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/index.php

Results:

Table 6-11 shows the projected changes in annual energy expenses for irrigation pumping, as compared to the baseline, for the two RCPs and three eras. Irrigation water requirements increase compared to the baseline for all eras and RCPs, ranging from a 15 percent increase in the mid-century to 39 percent increase in the late century for RCP8.5. The increase in irrigation water requirements drives the rising costs.

TABLE 6-11. ANNUAL ECONOMIC IMPACTS RELATED TO INCREASED IRRIGATION PUMPING AS A RESULT OF CLIMATE CHANGE ($MILLION)

Impacts are defined as increased average energy costs of irrigation pumping, relative to a climate baseline of 1986-2005, for five crops in Delaware, measured in millions of dollars (2019) per year and averaged over 5 GCMs. Irrigated crops include corn, soybeans, barley, hay, and wheat. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$0.25	$0.31	$0.34	$0.30	$0.60	$0.20
New Castle County	$0.15	$0.22	$0.21	$0.21	$0.36	$0.14
Sussex County	$0.42	$0.65	$0.58	$0.55	$1.0	$0.44
Delaware Total	**$0.83**	**$1.2**	**$1.1**	**$1.1**	**$2.0**	**$0.79**

Limitations:

- This analysis assumes farmers who irrigate now will be able to irrigate under future conditions. We do not take into account pumping capacities that may restrict the amount of water pumped without upgrading to higher capacity pumps or digging new wells.
- We assume irrigated areas are constant into the future and that the crop mix remains constant, as well. We also assume that energy prices per unit of energy will be constant in 2019 dollars, but all of these factors are likely to change in the future.
- The irrigation pumping costs assume that pumping depths remain constant. In cases of prolonged drought, water tables may drop, further increasing the energy required to irrigate from wells.
- Damages to yields or loss of irrigated acreage from saltwater intrusion are not considered in the damages in this section. See Chapter 6.1 for an analysis that considers these impacts.

6.4 AGRICULTURAL LABOR

Lost wages in agriculture sector due to fewer hours worked on high heat days

Climate change is projected to increase average temperatures and produce more high-heat days which can be dangerous for workers in climate-exposed conditions. Agricultural workers are projected to work fewer hours on days with temperatures above 90 degrees, resulting in lost wages and productivity. In this analysis, we rely on results from a previous study that estimates the impact of high-heat days on hours worked in high-risk industries.

Methods:

Neidell et al. (forthcoming)[141] estimate the average change in hours worked per high-risk worker in response to high temperatures. This study, which is an update of Graff-Zivins and Neidell (2014) cited in the 2017 U.S. EPA Climate Change Impacts and Risk Analysis report, uses the American Time Use Survey data for the period 2003 through 2018 and historical weather data to model the relationship between daily temperature and time allocation, focusing on hours worked by high-risk laborers (which includes workers in agriculture, construction, manufacturing, mining, and transport and utilities). Examining the effect across three segments of the observed time period, Neidell et al. found that high-heat events have a significant effect on hours worked both before and after the Great Recession (2008-2014) but no effect during the recession period. During periods of economic growth, the authors find for every degree above 90 on a particular day, the average high-risk worker reduces their time devoted to work by about 2.6 minutes relative to a 90-degree (or cooler) day. This modeled relationship between hours worked and high heat days during non-recession periods is used to project losses under future climates; projections are adjusted for future recessions by assuming a continued likelihood of economic growth in the future and multiplying future losses by proportion of observed expansion over the last 50 years (86.2 percent).[142]

In this analysis, we use the effect estimated by Neidell et al. and apply it to the number of agricultural workers in Delaware and average wages to estimate the lost wages associated with reduced hours on high-heat days.

The data sources used in this analysis are summarized in **Table 6-12**.

TABLE 6-12. AGRICULTURAL LABOR ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
DE agricultural wage rates	Mean hourly wage for agricultural workers in Delaware	U.S. Bureau of Labor Statistics. 2018. Occupational Employment and Wages, May 2018. https://www.bls.gov/oes/2018/may/oes450000.htm
DE agricultural workers	County-level estimates of agricultural workers in Delaware	American Community Survey 2008-2012. https://nhgis.org/

---

[141] Neidell, M., Graff-Zivins, J., Sheehan, M., Willwerth, J., Fant, C., Sarofim, M., and Martinich, J. Forthcoming. Temperature and work: Time allocated to work under varying climate and labor market conditions. Submitted to PLOS ONE November 2020.

[142] The National Bureau of Economic Research. US Business Cycle Expansions and Contractions [Internet]. Cambridge, MA [updated 8 June 2020; cited 15 September 2020]. Available from: https://www.nber.org/cycles.html.

Results:

The results in **Table 6-13** represent the projected lost wages to agricultural workers in Delaware on days above 90 degrees. Future projections account for the probability of economic recessions, during which no impacts were observed in Neidell et al. (forthcoming) by multiplying results by the proportion of observed expansion over the last 50 years (86.2 percent).[143] These results also assume the number of agricultural workers in Delaware remains constant over the century, which is consistent with national projections through 2028.[144] The highest impacts are projected to take place in Sussex County, where the majority of agricultural labor occurs. Late century impacts of $0.6 to $1.8 million under RCP4.5 and RCP8.5, respectively, represent 0.4 to 1.1 percent of total annual agricultural wages in Delaware.[145]

TABLE 6-13. ANNUAL ECONOMIC IMPACTS TO AGRICULTURAL LABOR FROM CLIMATE CHANGE ($MILLION)

Impacts are defined as lost wages for agricultural work hours lost due to high heat days, relative to a 2008-2012 baseline number of Delaware agricultural worker hours, measured in millions of dollars (2019) per year, averaged over 6 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$0.056	$0.048	$0.14	$0.093	$0.46	$0.16
New Castle County	$0.054	$0.051	$0.14	$0.093	$0.46	$0.16
Sussex County	$0.11	$0.10	$0.27	$0.19	$0.86	$0.30
Delaware Total	**$0.22**	**$0.20**	**$0.55**	**$0.38**	**$1.8**	**$0.62**

Limitations:

- This analysis does not account for productivity or welfare losses, or potential adverse health outcomes for workers who continue to work during high-heat events. We also do not account for extreme precipitation or other weather events that might preclude agricultural work.
- This analysis does not capture instances of temporal substitution of work across days, meaning workers who put in extra hours on the days before or after a high-heat event. It does, however, capture intra-day substitution, or workers who extend their days into the earlier or later parts of the day to avoid the maximum temperature period.
- The estimate of hours lost per worker from Graff-Zivins et al. (2014) (i.e., 2.6 minutes per degree day) was developed based on data for a larger set of high-risk industries, including agriculture, construction, manufacturing, and other primarily outdoor or climate-exposed industries. The specific effect on agricultural labor supply may differ from the average effect across all industries.

---

[143] The National Bureau of Economic Research. US Business Cycle Expansions and Contractions [Internet]. Cambridge, MA [updated 8 June 2020; cited 15 September 2020]. Available from: https://www.nber.org/cycles.html.

[144] U.S. Bureau of Labor Statistics. 2020. Available at https://www.bls.gov/emp/tables/employment-by-major-industry-sector.htm

[145] Assuming an average of 2080 hours worked per year.

6.5 CURRENT AND PREDICTED INVASIVE AND NUISANCE SPECIES

Control of current and predicted invasive and nuisance species in relation to herbicide and pesticide usage

Invasive and nuisance species have a negative effect on U.S. agricultural production, and managing them requires the application of pesticides and herbicides. Although few studies have been conducted to monetize these effects, Pimentel et al. (2005) suggest annual losses of $40 billion nationally in crop and forest production due to invasive species and pathogens.[146] Other studies have demonstrated that climate change is likely to increase the spread of invasive and nuisance species as warming occurs and precipitation patterns shift (e.g., research by Dukes et al., 2009 and Ziska et al., 2011).[147] In Delaware, the most concerning invasive and nuisance species are currently johnsongrass (*Sorghum halepense)*, Canada thistle *(Cirsium arvense*), burcucumber (*Sicyos angulatus*), giant ragweed (*Ambrosia trifida*), Texas panicum (*Panicum texanum*), and palmer amaranth (*Amaranthus palmeri*), although this list is likely to expand under a warming climate.[148]Insufficient information is readily available to monetize the effects of climate change on invasive and nuisance species costs on Delaware's agricultural production. Here, we briefly illustrate one possible set of analytical steps for such an evaluation, along with a list of data gaps.

Methods:

We illustrate an approach that relies on bioclimatic envelope modeling, following the process previously described in the section on invasive species management (Chapter 3.4).[149] A summary of that process tailored to the agricultural context follows below. Broadly, understanding how climate change may affect the spread of invasive species requires information on both the current spatial extent of each species, and the bioclimatic requirements of the species. Together, these would allow us to use bioclimatic envelope modeling to understand how the cropped area affected by invasive and nuisance species will be affected.

1. **Select plant species for analysis**. The criteria for the inclusion of a species are sensitivity to climate change, non-prevalence across Delaware in the baseline period, and available data on the existing range and bioclimatic requirements. None of the invasive and nuisance species above met the third criteria (i.e., none of them have range and bioclimatic requirements available), so this is information that will be needed in order to follow the approach described here.

---

[146] Pimentel, D., R. Zuniga, D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics. 52:273-288.

[147] Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., … and J. Ehrenfeld. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? One of a selection of papers from NE Forests 2100: A Synthesis of Climate Change Impacts on Forests of the Northeastern US and Eastern Canada. Canadian Journal of Forest Research 39(2):231-248.;

Ziska, L., D. Blumenthal, G. Runion, E. Hunt Jr., and H. Diaz-Soltero. 2011. Invasive species and climate change: an agronomic perspective. Climatic Change. 105:13-42.

[148] Delaware Department of Agriculture. Noxious Weeds. Available at https://agriculture.delaware.gov/plant-industries/noxious-weeds/

[149] Bioclimatic envelope modeling uses climate data within the current observed range of a species to bracket suitable climate conditions, and then analyzes climate data over a broader region to assess the areas that are (a) suitable for the species currently, and (b) will be suitable under future climate conditions. The difference between (a) and (b) is the potential impact of climate change on the species' ranges, which unlike invasive and nuisance species, are likely to contract for native species. Bioclimatic requirements for a species to survive and reproduce may include, for instance, sustained maximum daily temperatures under a threshold, or a minimum monthly level of rainfall.

2. **Develop bioclimatic envelopes that describe suitable habitat conditions for representative species.** To establish suitable habitat for the species, spatial data on existing habitat area and information on bioclimatic requirements are needed. Baseline climate data would be overlain on the areas of existing habitat to define ranges for each bioclimatic requirement that constrain suitable habitat.
3. **Determine potentially suitable habitat range using baseline and future climate conditions.** The next step would determine the area where bioclimatic conditions are met for each species selected in Step 1, using historical climate data. The current invaded range is likely to be considerably smaller than the full potential invaded range due to non-climatic constraints. A similar process would be conducted for each selected climate scenario to understand the areas that become suitable given future climate change.
4. **Calculate cropped area in Delaware where species control is needed.** Next, the ratio of projected to baseline suitable area would be multiplied by the observed cropped area affected by nuisance and invasive species. This provides an estimate of the additional area under climate change where control may be needed.
5. **Apply per acre costs to control species.** Options to control invasive and nuisance species may include mechanical removal, chemical treatment, or other methods. The magnitude of these costs may be wide-ranging depending on the specific species being targeted. On the low end, the phragmites control program administered by the Delaware Department of Natural Resources and Environmental Control's (DNREC) Division of Fish and Wildlife spends $300,000 per year for approximately 6,000 acres, or $50 per acre. Other management costs are likely to be considerably higher.[150]

The data sources need to conduct such an analysis are summarized in **Table 6-14**.

---

[150] Note that per acre costs can also be considerably higher than the phragmites control program. In a study for the Department of Interior, IEc found that Chinese tallow treatments are approximately $25,000/acre for a seven-year program [CTTF (Chinese Tallow Task Force). 2005. Chinese Tallow Management Plan for Florida, 1st ed. C.M. McCormick, Chair. Florida Exotic Pest Plant Council. 83 pp.], and Cogongrass treatments are roughly $5,000/acre for a four-year program [McClure, M., and J. Johnson. 2010. Cogongrass eradication strategies. Georgia Forest Commission. 3 pp., Alabama Forestry Commission. 2012. Final Report of the American Reinvestment and Recovery Act, Award Number 09-DG-11084419-041 – ARRA, Cogongrass Program (Alabama Cogongrass Control Center). Submitted by Larson & McGowin, Inc. 77pp.].

TABLE 6-14. INVASIVE PLANT SPECIES ON CROPLAND ANALYSIS DATA SOURCES AND NEEDS

DATA	DESCRIPTION	POTENTIAL SOURCE AND/OR EXAMPLES
Climatic variables	A gridded climate dataset that provides daily temperature and precipitation under baseline and future climate scenarios, which are needed to model bioclimatic requirements	Pierce, D. W., Cayan, D.R. and Thrasher, B.L. 2014. Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology. 15, 2558-2585.
Species of concern	The set of species that are selected for the analysis	DDA and DNREC.
Species range	County-level data on invaded species range	Clark, T. 2015. A subcontinental reconstruction of invasion patterns and processes for the past two centuries. M.S. Thesis, Purdue University.
Bioclimatic variables	Species-specific climatic variables that constrain the habitat range of the nuisance and invasive species	Examples for two invasive species are provided in Chapter 3.4.
Crop areas affected by species of concern	Acres of cropland in Delaware, broken down by county	U.S. Department of Agriculture National Agricultural Statistics Service. 2017. NASS – Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-statshttps://data.nal.usda.gov/dataset/nass-quick-stats. Area affected by nuisance and invasive species from DDA and/or DNREC.
Per acre invasive and nuisance species control cost	The per acre management costs	DDA and DNREC, Division of Fish and Wildlife.

Although insufficient information was available to conduct this analysis, the above steps and data needs provide one approach to estimating the economic impacts of climate change on agricultural nuisance and invasive species management.

6.6 MILK PRODUCTION IN DAIRY COWS

Milk production in dairy cows due to higher temperatures

Dairy cows are sensitive to heat, humidity, and the resulting proliferation of parasites and pests. As a result, these threats could reduce Delaware's milk production significantly under climate change.[151] We used results from a study on how climate change affects milk production in the U.S.[152] to project losses in Delaware's future milk revenues.

Methods:

Based on a literature review of recent studies, Mauger et al. (2015) appear to have the most geographically relevant and recent results that can be transferred to Delaware. Although Hayhoe et al. (2014) report that by mid-century, climate-related threats could reduce Delaware's milk production by 10 to 25 percent, this finding appears to be transferred from a much earlier article from 2006. Mauger et al. relate historical and projected climatic variables to milk production using a biophysical approach, and develop estimates at 10 locations across the U.S. We transfer information from their Lancaster, PA location, with the analysis taking the following steps:

1. **Estimate lost milk production.** Mauger et al. found that due to climate change, milk loss per cow would be approximately 2.1 pounds per day (lbs/day) by the 2050s and 3.2 lbs/day by the 2080s, relative to a 1950-1999 baseline. Given the average annual milk production in Delaware is approximately 90.5 million lbs over the 2015-2019 period, with a total of 4,500 milk cows in 2017[153]; milk production per cow in Delaware is approximately 66 lbs/day assuming 300 days of production per year. This per cow milk production value is identical to the value used by Mauger et al.
2. **Map projected changes in temperature to Mauger analysis.** The Mauger et al. study relied on the A1B emissions scenario from the Special Report on Emissions Scenarios in the International Panel on Climate Change's 4th Assessment.[154] Although we rely on the more recent RCP4.5 and RCP8.5 trajectories, the A1B emissions trajectory is approximately halfway between the two RCPs we rely upon. Although Mauger et al. do not present their A1B temperature changes for Lancaster, we assume that average temperatures across the 6 GCMs and 2 RCPs in our mid- and late century scenarios (i.e., 2040-2059 and 2080-2099) are approximately equal to the A1B temperature levels in the Mauger et al. 2050s and 2090s. These are approximately 4.5°F and 7.4°F, respectively.
3. **Estimate lost milk production under climate change in Delaware.** With these hinge points between our temperature projections and those from Mauger et al., we translated county-level Localized Constructed Analogues (LOCA) projections of temperature

---

[151] Hayhoe, K., Wake, C., Huntington, T., Luo, L., Schwartz, M., Sheffield, J., … Wolf, D. (2006). Past and future changes in climate and hydrological indicators in the US Northeast. 2006 Climate Dynamics. doi:10.1007/ s00382-006-0187-8. We anticipate wishing to consult with DDA as part of the kickoff meeting to better understand whether these estimates remain reasonable for Delaware.

[152] Mauger G., Y. Bauman, T. Nennich and E. Salathé. 2015. Impacts of Climate Change on Milk Production in the United States, The Professional Geographer, 67:1, 121-131, DOI: 10.1080/00330124.2014.921017.

[153] U.S. Department of Agriculture National Agricultural Statistics Service. (2017). NASS - Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats. Accessed 2020-12-04

[154] IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

changes for the six GCMs, two RCPs, and three eras to losses in milk production per cow (from Mauger et al.). Then we converted it to percent reductions in milk production using the average milk production per cow from Step 1.

4. **Estimate economic losses.** Lastly, we estimate the effect on total county-level milk production in Delaware, by multiplying the percent reductions from Step 3 by the total 2017 milk production revenues reported by the U.S. Department of Agriculture. Total revenues are approximately $17 million across Delaware, of which $7.1 million is in Kent County, $1.9 million is in New Castle County, and $7.8 million is in Sussex County.

The data sources used in this analysis are listed in **Table 6-15**.

TABLE 6-15. MILK PRODUCTION ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Climatic variables	The LOCA dataset provided temperature projections under the baseline and future climate scenarios, which we used for milk production loss estimation	Pierce, D. W., Cayan, D.R. and Thrasher, B.L. 2014. Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology. 15, 2558-2585.
Milk loss per cow	Reduction in milk production per cow under climate change	Mauger G., Bauman, Y., Nennich, T. and Salathé, E. 2015. Impacts of Climate Change on Milk Production in the United States. The Professional Geographer. 67:1, 121-131.
Revenues from milk production	Data on milk production revenues in 2017, used to estimate total losses under climate change	U.S. Department of Agriculture National Agricultural Statistics Service. 2017. NASS – Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats
Milk production and number of milk cows	Used to estimate the average milk produced per cow per day in Delaware, average of five years of milk production data between 2015 and 2019, count of cows from 2017	

Results:

Figure 6-4 presents the projected percentage reduction in milk production under each climate scenario and era, averaged across the six GCMs. The maximum change, which occurs under RCP8.5 in the late century, shows an approximate six percent reduction in milk production relative to current conditions. Differences between counties are driven by temperature projections, which differ minimally at the county scale.

FIGURE 6-4. REDUCTION IN MILK PRODUCTION UNDER EACH CLIMATE SCENARIO AND ERA

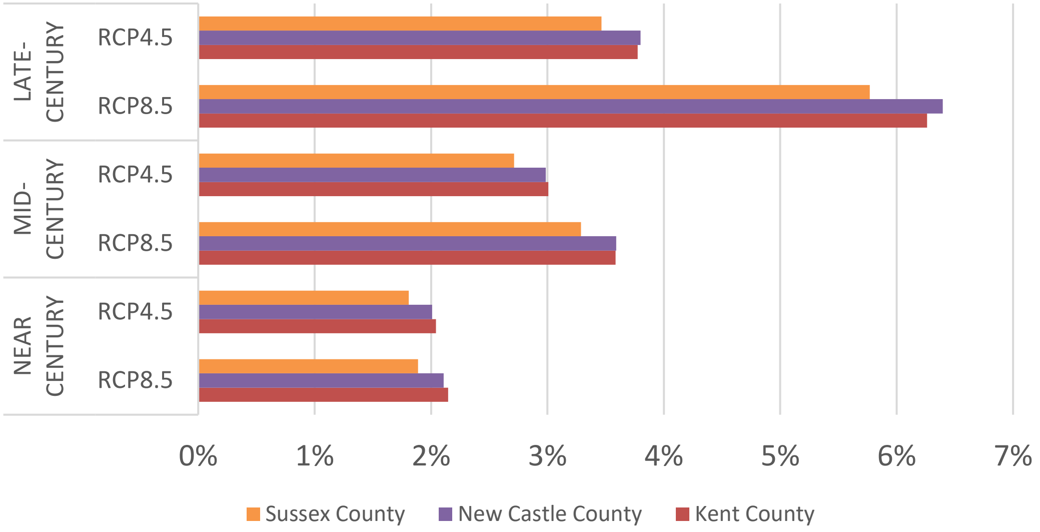


Table 6-16 shows the projected reduction in annual revenues from milk production relative to the $17 million in 2017 statewide revenues. The impacts range from approximately $320,000 to $1.0 million. Kent and Sussex counties are generally affected similarly, at up to $450,000 by late century, whereas New Castle county bears lower impacts because of its much smaller population of dairy cows.

TABLE 6-16. ANNUAL ECONOMIC IMPACTS TO MILK PRODUCTION DUE TO CLIMATE CHANGE ($MILLION)

Economic impacts are defined as reduction in revenues from milk production relative to the baseline climate scenario (1986-2005), measured in millions of dollars (2019) per year. Results reflect the average of 6 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$0.15	$0.14	$0.25	$0.21	$0.44	$0.27
New Castle County	$0.39	$0.37	$0.67	$0.55	$0.12	$0.07
Sussex County	$0.15	$0.14	$0.26	$0.21	$0.45	$0.27
Delaware Total	**$0.34**	**$0.32**	**$0.58**	**$0.48**	**$1.0**	**$0.61**

Limitations:

- Although the climate modeling and milk production data were specific to Delaware, we relied on modeling of milk production impacts from a neighboring state. The analysis could be refined with more spatially explicit modeling of Delaware dairy farms.
- This analysis ignores adaptive actions that may be taken by farmers, including cooling and ventilation systems that may reduce heat.

- Although we believe the Mauger et al. study is most relevant to this context, relying on the Hayhoe et al. work would produce considerably larger damages – their high-end milk production impact estimate of 25 percent by mid-century is approximately six times higher than our mid-century estimates.
- The analysis does not consider parasite or pest impacts, both of which may be intensified with climate change. If included, these would drive the impact costs upward.
- As these impact estimates are percentages relative to 2017 production levels, if production were to change significantly in the future, the dollar impact values would scale accordingly.

6.7 POULTRY FARM ENERGY DEMANDS AND INFRASTRUCTURE NEEDS

Poultry farms will see changes in their cooling and heating demands as climate changes, and poultry farm infrastructure may need to be adapted or replaced to limit mortality and ensure continued high production during extreme heat events and heat waves

In 2019, Delaware produced 269 million broilers at a value of over $940 million per year.[155] Broiler production occurs in indoor facilities which shelter chickens from weather and predation and allow for environmental controls (e.g., heating and cooling) resulting in the desired level of productivity. Based on discussions with DDA, we understand that all, or nearly all, indoor facilities have some manner of temperature control. As temperatures rise and extreme heat events become more frequent and severe under climate change, the energy demands of these environmental control systems will shift. Furthermore, there will be cases for which current cooling systems, even run at higher levels, will not be sufficient, necessitating upgrades to systems.

To capture the effects of climate change, our primary analysis assumes current infrastructure is satisfactory and calculates the costs of changes in energy demand and resource usage, represented by a balance between increased demand on electric cooling systems and decreased demand on propane heating systems.[156] We also qualitatively note that if current infrastructure is not satisfactory, there are likely to be significant costs of upgrading it to new systems.

Methods:

In order to estimate change in heating and cooling costs, we assume the use of current infrastructure and focus on energy demands by these systems. First, we estimate the baseline annual heating and cooling costs per square foot of chicken house area and multiply this by the total area of chicken houses in each of Delaware's three counties (see Table 6-18).[157]

Details on the heating and cooling cost calculations:

- **Annual heating costs:** We use data from the University of Arkansas (Tabler et al. 2020), with values corroborated by other publications (e.g., annual propane demand was checked against Baranyai and Bradley 2008), to calculate annual heating costs in dollars per square foot.[158,159] Tabler et al. validate our assumption that all propane demand is attributable to heating infrastructure. We then multiply this value by the chicken house area of each Delaware county to obtain baseline heating costs.
- **Annual cooling costs:** We use a published Broiler Budget out of the University of Maryland Extension (University of Maryland, 2017) to obtain a value for annual cost of

---

[155] U.S. Department of Agriculture NASS Production and Value 2019 Summary. https://downloads.usda.library.cornell.edu/usda-esmis/files/m039k491c/jq086502q/rn301m63j/plva0420.pdf

[156] Note that these costs represent adaptation costs rather than climate change impacts.

[157] The Delmarva Index and Eastern Shore Regional GIS Cooperative 2020. Delmarva Chicken Houses. June, delmarvaindex.org/result/5e8ccb346036f30018e0d7d4.

[158] Tabler, G.T., Berry, I.L., and Mendenhall, A.M for the University of Arkansas's Avian Advice. 2020. Energy Costs Associated with Commercial Broiler Production. The Poultry Site, 4 Dec. www.thepoultrysite.com/articles/energy-costs-associated-with-commercial-broiler-production.

[159] Baranyai, Vitalia, and Sally Bradley. 2008. Turning Chesapeake bay watershed poultry manure and litter into energy: An analysis of the impediments and the feasibility of implementing energy technologies in the Chesapeake bay watershed in order to improve water quality. Chesapeake Bay Program: A Watershed Partnership. CBP/TRS-289-08. https://www.chesapeakebay.net/documents/cbp_17018.pdf

electricity per square foot.[160] We then scale this number using graphs from the University of Arkansas indicating that about half of electricity demand cannot be attributed to cooling demand, but instead to other requirements such as feed lines and lighting. We finally multiply this value by the chicken house area of each Delaware county to obtain baseline cooling costs.

Table 6-17 summarizes estimated annual heating and cooling costs, as well as inputs to the calculations.

TABLE 6-17. BASELINE HEATING AND COOLING COSTS

The heating and cooling costs are in 2019 dollars, based on the prices of propane (per gallon) and electricity (per kWh) from the Energy Information Administration. Annual heating and cooling costs are simply chicken house area in square feet, multiplied by the cost per square foot of heating and cooling. Values may not sum due to rounding.

	KENT COUNTY	NEW CASTLE COUNTY	SUSSEX COUNTY	TOTAL FOR DELAWARE
Chicken House Area (sq ft)	16,734,000	638,000	40,154,000	57,526,000-
Annual Heating Cost ($/sq ft)	$0.32			
Annual Cooling Cost ($/sq ft)	$0.13			
Annual Heating Cost ($)	**$5,415,000**	**$206,400**	**$12,994,000**	**$18,615,400**
Annual Cooling Cost ($)	**$2,092,000**	**$79,700**	**$5,019,000**	**$2,171,700**

In order to estimate how heating and cooling costs may change in the future, we use the LOCA climate projection dataset to estimate the change in heating degree days and cooling degree days, which are metrics commonly used for energy use calculations.[161] Heating degree days are calculated as the total number of degrees each day below 65 degrees. For example, if day 1 is 35 degrees and day 2 were 25 degrees, the heating degree days for those two days would be 70 "degree-days". Cooling degree days are the same calculation but for degree-days above 65 degrees. This metric is widely used in the energy industry to understand the building heating and cooling requirements in a given region.

To estimate energy costs under climate change, we scale baseline heating costs by the ratio of heating degree days under climate change to heating degree days under the baseline, and baseline cooling costs using the same calculation with cooling degree days. For example, if cooling degree days are expected to increase by 10 percent through the early century under a particular GCM and emissions scenario, the annual cooling costs would increase by approximately $210,000 (i.e., 10 percent of $2.1 million, with $2.1 million sourced from **Table 6-17** above).

The data sources used in this analysis are listed in **Table 6-18**.

---

[160] University of Maryland. 2017. Broiler Budget. University of Maryland Extension, 2017, extension.umd.edu/lesrec/marylands-poultry/broiler-budget.

[161] Kucuktopcu, E., B. Cemek, and P. Banda. 2017. Determination of poultry house indoor heating and cooling days using degree-day method. Agronomy Research 15.3: 760-766.

TABLE 6-18. POULTRY HEATING AND COOLING ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE(S)
Chicken house area (sq ft per county)	Delmarva Chicken Houses spatial dataset, developed by the Eastern Shore Regional GIS Cooperative; identifies locations and operational status of chicken houses for fourteen Delmarva counties	The Delmarva Index and Eastern Shore Regional GIS Cooperative. 2020. Delmarva Chicken Houses. https://delmarvaindex.org/result/5e8ccb346036f30018e0d7d4
Annual propane demand (gallons per sq ft)	This study provides propane demand per chicken house and per chicken house square foot Propane demand data are corroborated by the Chesapeake Bay Program Office	Primary: Tabler, G.T., Berry, I.L. and Mendenhall, A.M for the University of Arkansas's Avian Advice. 2020. Energy Costs Associated with Commercial Broiler Production. www.thepoultrysite.com/articles/energy-costs-associated-with-commercial-broiler-production Corroboration: Baranyai, Vitalia and Bradley. 2008. Turning Chesapeake bay watershed poultry manure and litter into energy: An analysis of the impediments and the feasibility of implementing energy technologies in the Chesapeake bay watershed in order to improve water quality. Chesapeake Bay Program: A Watershed Partnership. CBP/TRS-289-08. https://www.chesapeakebay.net/documents/cbp_17018.pdf
Cost of propane ($ per gallon)	The Energy Information Administration provides wholesale propane costs for winter months over the last five years Propane costs for farmers corroborated by the University of Arkansas Avian Advice and the Chesapeake Bay Program Office	Primary: U.S. Energy Information Administration. 2020. Weekly Heating Oil and Propane Prices (October - March) (Dollars per Gallon Excluding Taxes). https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPLLPA_PWR_dpgal_w.htm Corroboration: Tabler, G.T., Berry, I.L., and Mendenhall, A.M for the University of Arkansas's Avian Advice. 2020. Energy Costs Associated with Commercial Broiler Production. www.thepoultrysite.com/articles/energy-costs-associated-with-commercial-broiler-production
Annual electricity costs ($ per sq ft)	University of Maryland Extension cash flow and enterprise budget for poultry growers	University of Maryland. 2017. Broiler Budget. University of Maryland Extension. extension.umd.edu/lesrec/marylands-poultry/broiler-budget
Fraction of electricity used for cooling	Time-series graphs allows us to make assumptions about the fraction of electricity used for cooling, which only occurs in hotter temperatures, as compared to baseline costs for lighting, feed lines, etc.	Tabler, G.T., Berry, I.L., and Mendenhall, A.M for the University of Arkansas's Avian Advice. 2020. Energy Costs Associated with Commercial Broiler Production. www.thepoultrysite.com/articles/energy-costs-associated-with-commercial-broiler-production
Climatic variables	The LOCA dataset provides daily minimum and maximum temperature under baseline and future climate scenarios, which we average to produce average temperature and calculate annual heating degree days and cooling degree days	Pierce, D. W., Cayan, D.R. and Thrasher, B.L. 2014. Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology. 15, 2558-2585.

Results:

Table 6-19 presents projected annual changes in energy costs due to climate change, averaged over the six GCMs used in this study. These total annual cost changes are the result of the summation of decreases in the cost of heating and increases in the cost of cooling, which are especially sensitive to the price of fuel (electricity and propane), as well as the fuel demand per unit area. Overall, we see up to a $2.3 million net increase in energy costs under the late century RCP8.5 projection, suggesting that on average increases in cooling costs will exceed decreases in heating costs.

TABLE 6-19. ANNUAL ECONOMIC IMPACTS TO POULTRY FARM ENERGY COSTS DUE TO CLIMATE CHANGE ($MILLION)

Impacts are defined as changes in energy costs defined as increased poultry industry expenditures relative to the baseline climate scenario (1986-2005), measured in millions of dollars (2019) per year and averaged over 6 GCMs. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY[a] (2040-2059)		LATE CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County	$0.091	$0.081	$0.14	$0.044	$0.71	$0.12
New Castle County	$0.006	$0.005	$0.010	$0.005	$0.034	$0.009
Sussex County	$0.34	$0.31	$0.40	$0.23	$1.5	$0.35
Delaware Total	**$0.43**	**$0.40**	**$0.55**	**$0.28**	**$2.3**	**$0.48**

Note:

a. Under RCP4.5, we see a drop in costs from near century to mid-century, and then a rise to late century. When viewed separately, changes in heating degree days and cooling degree days, and thus heating costs and cooling costs, do individually decrease and increase smoothly in the expected directions over time. However, the net costs do not increase smoothly.

Limitations:

- Our analysis does not consider the costs for any changes needed in cooling infrastructure, for example a shift from evaporative cooling to air conditioning, or investment in better housing insulation. Although estimating their occurrence was out of the scope of this analysis, such infrastructure investments are likely to be needed for some chicken houses as temperatures rise.[162]
- This analysis does not include the impacts of other climate stressors (i.e., frequent or permanent inundation due to SLR).
- The analysis assumes that sufficient water will continue to be available to meet increased evaporative cooling requirements. If water is not available, it may be necessary to switch to air conditioning rather than evaporative cooling, which would be costly in terms of energy use and capital costs.

---

[162] Reay D. 2019. Climate-Smart Chicken. In: Climate-Smart Food. Palgrave Pivot, Cham. https://doi.org/10.1007/978-3-030-18206-9_9; Izar-Tenorio, Jorge, et al. 2020. Impacts of projected climate change scenarios on heating and cooling demand for industrial broiler chicken farming in the Eastern US Journal of Cleaner Production 255: 120306.

- Further, the study does not consider the cost of pumping groundwater for cooling. Currently most poultry houses use swamp coolers (evaporative cooling) which rely on pumping groundwater. As cooling costs increase, pumping costs will also increase.
- A recently published paper uses thermodynamic modeling to conduct a similar evaluation for broiler houses in the Eastern United States, with case studies for the Southeast that find that reductions in heating energy demand outweigh increased cooling energy demand.[163] Although we do not have access to the detailed methods applied in this study, this difference from our results can likely be attributed to climatic differences between study areas, and the methodology involved in translating temperature changes to monetized energy effects.
- We assume that cooling requirements vary only due to climatic conditions, without taking into account how optimal temperatures vary across broiler life stages.
- The analysis does not consider the possibility of genetic improvements in poultry breeds that would increase heat tolerance. Such improvements may allow for production at a broader range of temperatures and thus reduce cooling energy requirements.

---

[163] Izar-Tenorio, Jorge, et al. 2020. Impacts of projected climate change scenarios on heating and cooling demand for industrial broiler chicken farming in the Eastern US Journal of Cleaner Production 255: 120306.

CHAPTER 7 | PUBLIC SAFETY IMPACTS (DSHS)

The Delaware Department of Safety and Homeland Security (DSHS) promotes and protects the safety of people and property in Delaware. Understanding how climate change may affect the security of the state could allow DSHS to more effectively plan and allocate key resources and capacity. Climate change poses several risks to public safety, including:

1. **Emergency services response time** to emergencies, if roadways are impassible due to flooding or damage.
2. **Access and upkeep of evacuation routes**, in terms of mortality risk of coastal flooding events.
3. **Frequency of emergency responses** due to increased flooding and storms.
4. **Limited access to cooling by vulnerable populations** during extreme temperature events and heat waves.

Impacts in this sector include direct costs (e.g., cost of emergency response and structure damage) and welfare losses due to fatal risk. **Table 7-1** presents annual results by impact category for both RCPs analyzed (RCPs, or representative concentration pathways, correspond to different emissions scenarios; see Chapter 2.1 for further details). The largest impacts are related to emergency services response time, as slower response times (due to road damages and flooding) result in higher mortality rates. Impacts across all categories increase significantly between mid- and late century.

TABLE 7-1. ANNUAL STATEWIDE ECONOMIC IMPACTS TO PUBLIC SAFETY CATEGORIES ($MILLION)

Figures represent total statewide impacts by RCP (for categories impacted by changes in temperature and precipitation) or by era only (for categories impacted by SLR, excluding storm surge) in millions of dollars (2019). As this table presents annual impacts, storm surge impacts are not included, as such impacts are estimated on a per-event basis. For further information on each category, please see Chapters 7.1 through 7.4.

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
7.1	Emergency services response time[a]	$16	$8.9	$17	$12	$27	$16
		$0.58		$5.2		$77	
7.2	Access and upkeep of evacuation routes[b]	-					
7.3	Frequency of emergency responses[c]	$0.007	$0.007	$0.007	$0.007	$0.009	$0.007
7.4	Limited access to cooling for vulnerable populations	$3.9	$3.1	$7.6	$6.0	$55	$12

Notes:

a. The first row of emergency services response time impacts is presented by RCP and represent the impacts of temperature and precipitation. The second row represents the impacts of high tide flooding.
b. Impacts related to the access and upkeep of evacuation routes are summarized by storm surge event in Table 7-2.
c. Chapter 7.3 also includes illustrative impact estimates from increased frequency of emergency responses during the 1% hurricane event. See Table 7-12 for details.

Figure 7-1 shows the distribution of impacts across counties. New Castle County is projected to have the highest level of impacts, in large part due to its concentration of population and road networks.

FIGURE 7-1. PUBLIC SAFETY ECONOMIC IMPACTS BY COUNTY

Totals reported in millions of dollars (2019) represent temperature and precipitation-based impacts (RCP8.5 or RCP4.5) plus SLR impacts. As this figure presents annual impact values, totals do not include storm surge impacts, as such impacts are estimated on a per-event basis.

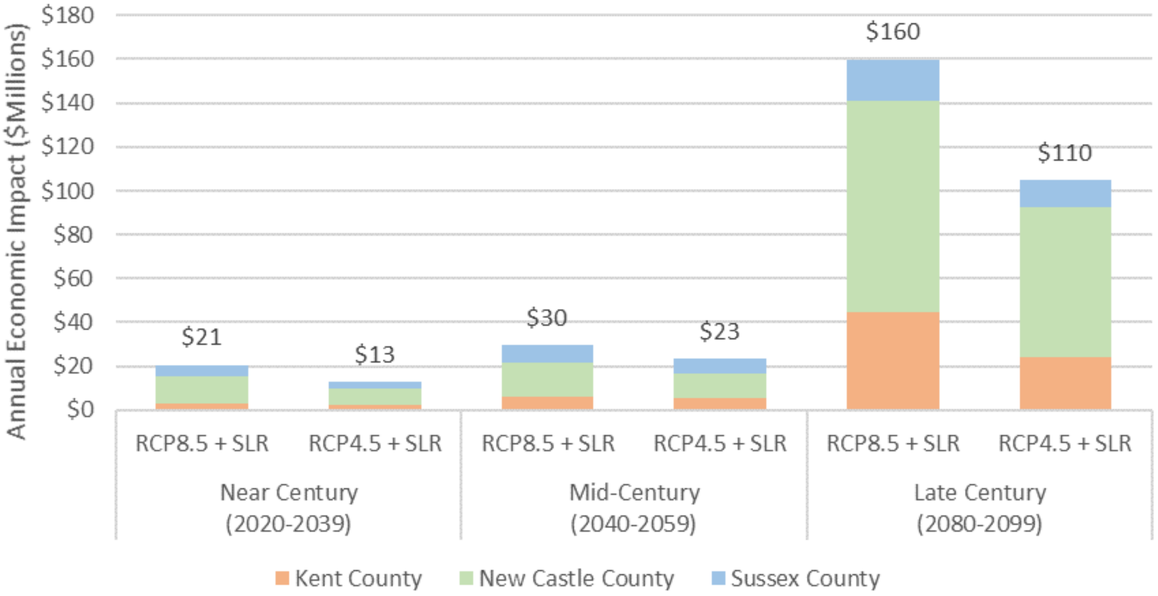


Table 7-2 presents impacts of storm surge events to emergency response time and evacuation route access and upkeep.

TABLE 7-2. STATEWIDE ECONOMIC IMPACTS TO PUBLIC SAFETY CATEGORIES FROM STORM SURGE EVENTS ($MILLION)

Impacts shown below result from 1-percent and 10-percent storm surge events, reported in millions of dollars (2019). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The below values represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year).

CATEGORY		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		10% Storm	1% Storm	10% Storm	1% Storm	10% Storm	1% Storm
7.1	Emergency services response time	$0.6	$1.4	$1.3	$3.0	$4.5	$6.4
7.2	Access and upkeep of evacuation routes	$0.001	$0.039	$0.003	$0.18	$0.060	$3.6

7.1 EMERGENCY SERVICES RESPONSE TIME

Emergency services response time to emergencies if roadways are impassible due to flooding or damage

Over the next century, climate change is expected to increase traffic delays, thereby reducing access to critical public safety services. Extreme temperature and precipitation events, which affect the structure and stability of roadways throughout the state, are projected to become more prolonged and frequent, increasing the need for road maintenance and repair. Coastal traffic delays will increase due to roads becoming impassable during high tide flooding events and the combined effects of sea level rise (SLR) and storm surge. These changes in traffic and road conditions will delay access to hospitals, emergency medical services (EMS), and fire response with consequences for increased mortality and property losses.

Methods:

We estimate the economic impacts for three critical public safety services – hospitals, EMS, and fire response – due to flooded or damaged roadways (as a result of either extreme temperatures and precipitation or high tide flooding and storm surge). We follow the 2016 benefit-cost methodology outlined by the Federal Emergency Management Agency (FEMA) to estimate the benefits of these critical services during an emergency.[164] In general terms, we use the FEMA methodology to calculate economic impacts of delayed responses in terms of mortality risk, property damage, and response costs as a function of emergency response frequency,[165] response delays attributable to climate change, and the relationship between delayed response and outcomes and costs.

The FEMA methodology provides a number of functions that relate mortality risk and response costs to emergency response time and frequency. This analysis utilizes these functions along with the following data: (1) total emergency response events per year; (2) calculation of delays in emergency response, due to extreme temperature and precipitation; and (3) high tide flooding and storm surge events, based on calculations of climate change impacts to transportation (see Chapters 5.1 and 5.4 of this report). Where Delaware specific data is not available, we use the national average data provided by FEMA.

1. Emergency Response Frequency. Calculating impacts on emergency services requires knowing the number of emergencies that occurred in areas with affected roadways. To determine the number of emergencies, we used national average data from FEMA on the per capita incidence rates of emergencies. We then converted per capita incidence rates to total number of emergencies using the Integrated Climate and Land Use Scenarios version 2 projections for population, as described in Chapter 2.1. We used the following methodology for each stressor:

- *Extreme temperature and precipitation*. The annual number of emergencies affected by extreme temperature and precipitation traffic delays were obtained by multiplying the

---

[164] U.S. Federal Emergency Management Agency (FEMA). 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

[165] Emergency response frequency is defined as the number of emergencies that occur during a particular time period that result in a response from an emergency service (e.g., a visit to a hospital emergency department, EMS response, or response from fire services). Following FEMA (2016), we assumed that the emergency response frequency is equal to the frequency of emergencies, both of which have units of number of incidents over time (e.g., number of heart attacks per day, number of calls to EMS for heart attacks).

annual per capita incidence values by the total county population.[166] No information was available about the average number of hours per year that roads are affected by extreme temperature and precipitation, so we assume extreme temperature and precipitation impacts are evenly distributed both throughout the state and over the average travel hours of the year (12 hours/day multiplied by the number of days in the year). Extreme temperature and precipitation effects on roads are also assumed to be distributed evenly throughout the state.

- *High tide flooding and storm surge*. The annual number of emergencies affected by high tide flooding are obtained by multiplying the annual per capita incidence values by the total county population, the proportion of the county population affected by the flooding event, and the average duration of the flooding event relative to the total number of hours in a year.[167]

2. Response delays attributable to climate change, including the impacts of extreme temperature, precipitation, high tide flooding, and storm surge. This analysis drew on FEMA's baseline response time data for fire services and EMS.[168] A baseline for the typical travel time to a hospital in Delaware was established using a 2018 report from the Pew Research Center.[169]

This analysis used estimates of traffic delays due to extreme temperature and precipitation, high tide flooding, and storm surge. Estimates of traffic delays from extreme temperature and precipitation (described in Chapter 5.1 of this report) were produced using information about key roads at risk of road closures due to damage from flooding or extreme heat and cold.[170] Estimates for traffic delays from increased high tide flooding and storm surge due to SLR were generated from inundation mapping results from the National Coastal Property Model using

---

[166] Annual per capita incidence values for each type of emergency came from FEMA (2016). Values for annual traffic per hour came from the transportation analysis (see Chapter 5.1).
FEMA. 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

[167] Values for the total proportion of the county population affected by high tide flooding and storm surge events were produced in the transportation analysis (see Chapter 5.4). We assume extreme temperature and precipitation affects the entire population of each county. Values for the average total annual duration of high tide flooding events were produced in the transportation analysis (see Chapter 5.4). The total annual duration of storm surge events is assumed to be 24 hours.

[168] For EMS and fire services, the analysis applied the typical response times as reported by the benefit-cost analysis in FEMA (2016). The typical response time of fire services to arrive at the scene of a structure fire is 5 minutes. The typical response time for EMS is 6 minutes in urban areas and 7 minutes in suburban areas. We assume that the EMS response time for urban areas applies to New Castle County, and the EMS response time for suburban areas applies to Kent and Sussex Counties.
FEMA. 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

[169] For hospitals, this analysis assumed a typical travel time of 13.3 minutes to a hospital in Delaware as reported for Mid-Atlantic states by a 2018 Pew Research Foundation Study.
Pew Research Center. 2018. How far Americans live from the closest hospital differs by community type. Retrieved from: https://www.pewresearch.org/fact-tank/2018/12/12/how-far-americans-live-from-the-closest-hospital-differs-by-community-type/.

[170] Estimates of extreme temperature and precipitation in Delaware were produced for this report (Chapter 2.2) using a suite of general circulation models (GCMs) from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) to look at two emissions scenarios: RCP4.5 and RCP8.5. Specifically, we rely on the Localized Constructed Analogues (LOCA) dataset for downscaled and bias corrected projections of the CMIP5 GCMs. Traffic delays resulting from extreme temperature and storm surge were produced as part of the transportation analysis and are described in Chapters 5.1 and 5.4.

information about key roads at risk of outage based on flood/water heights and elevation data (described in Chapter 5.4 of this report).[171]

Values for average county traffic (in vehicle miles per day), traffic delays (in vehicle miles per year), and the proportion of the population affected by flooding events were produced in the analysis of transportation impacts (see Chapters 5.1 and 5.4).). Using these data, we calculated the average delays per trip, (in minutes per mile) for extreme temperature and precipitation, high tide flooding, and storm surge. The average delays per vehicle (in minutes per mile) were multiplied by the typical trip distance for each emergency response category[172] in order to obtain the new response times, taking into account the travel delays due to extreme temperature and precipitation, high tide flooding, and storm surge. The travel delays were calculated as the difference between the new response times and the typical response times for each stressor, as follows:

- *Extreme temperature and precipitation*. Total annual traffic delays from temperature and precipitation (in vehicle hours per year) were divided by the total annual traffic (in vehicle miles per year, from the road delay analysis in Chapter 5.1) to obtain an estimate of the average delay per trip, in hours per mile.[173] We assumed that traffic impacted by temperature and precipitation delays are equal to typical traffic in each county.[174]
- *High tide flooding and storm surge*. To calculate the average delays per trip resulting from high tide flooding and storm surge, total annual traffic delays (in vehicle hours per year) were divided by the total event duration (in hours per year) to obtain an estimate of the total delay per hour (in vehicle hours per hour).[175] Data on total impacted traffic (in vehicle miles per hour) were reported at the state level, but high tide flooding and storm surge events predominantly affect people living near the coast. Total traffic data (in vehicle miles per hour) were adjusted to reflect traffic in the coastal areas by multiplying total traffic by the proportion of the population of the county affected by high tide flooding and storm surge.[176] An estimate of the average delay per vehicle (i.e., trip), in hours per mile, were obtained by dividing the total delay per hour by the adjusted total traffic (in vehicle miles per hour).

---

[171] Estimates of high tide flooding and storm surge were produced using one SLR projection pathway the National Coastal Property Model as the data source for inundation, as described in Chapter 2.3 of this report. Traffic delays resulting from high tide flooding and storm surge were produced as part of the transportation analysis and are described in Chapter 5.4.

[172] We used FEMA (2016) data on typical response times. We provide the response times for each emergency service elsewhere in this section.

[173] Total annual traffic in vehicle miles per year was calculated by multiplying total annual traffic in vehicle miles per hour by the total traffic hours in the year. For the purposes of the analysis of emergency services, traffic was assumed to occur primarily between the hours of 8am and 8pm, i.e., 12 out of the 24 hours in a day. The total traffic hours in a day (12 hours per day) was multiplied by the number of days in the year to obtain total traffic hours per year. These results were produced from the National Coastal Property Model for the transportation impacts analysis, as reported in Chapter 5.1.

[174] The values for total daily traffic (in vehicle miles per day) were calculated for the transportation analysis in Chapter 5 and are 211,878 for Kent County, 673,589 for New Castle County, and 306,704 for Sussex County. We assumed that traffic is evenly distributed across the roads in each county.

[175] We used estimates produced in the transportation analysis (see Chapter 5.4) for the total annual traffic delays for high tide flooding and storm surge events and average total annual duration of high tide flooding events. For storm surge events, we analyzed the annual impacts assuming a single, 24 hour-long event each year.

[176] The total proportion of the county population affected by high tide flooding and storm surge events were produced in the transportation analysis (see Chapter 5.1).

3. The relationship between delayed response, outcomes, and costs. We followed the 2016 benefit-cost methodology outlined by FEMA to estimate the benefits of fire station services, EMS, and hospitals during an emergency[177]:

- *Fire station services*. The FEMA approach relates the loss-of-function impact of firefighting services to the number of fire incidents in the area, the average value of losses per incident, and the change in fire service response time. This method calculates economic impacts of structural fires (i.e., the total value of losses) as the product of the probability of a no-loss structural fire, the number of structure fires affected by the delays, and the dollar value of total losses from structure fires.[178] The probability of a no-loss structural fire and the dollar value of total losses from a single structural fire (in 1993 dollars) are both calculated as functions of total response time (in minutes) and converted to 2019 dollars.[179] The number of structure fires affected by delays was calculated as the annual fire incidence per capita multiplied by the affected population and adjusted for the fraction of the year during which the roads were affected.[180] The economic impacts of travel delays on fire response times were calculated as the difference between the impact for the typical fire response times and the impact taking into account travel delays.
- *Emergency Medical Services*. The FEMA approach calculates the impacts of mortality from cardiac arrests due to changes to EMS response times (i.e., the time between collapse and EMS arrival) by multiplying the number of cardiac arrests in the area, the survival probability, and the Value of a Statistical Life (VSL). The survival probability of a cardiac arrest was calculated as a function of the time (in minutes) from collapse to CPR and the time (in minutes) from collapse to defibrillation.[181] The number of cardiac arrests was calculated by multiplying the annual incidence of cardiac arrests per capita by the affected population and adjusting for the fraction of the year during which the roads

---

[177] U.S. Federal Emergency Management Agency (FEMA). 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

[178] The FEMA methodology for fire services included direct property losses, indirect property losses, and losses from mortality and injury.

[179] The probability P_0 of a no-loss structural fire is $P_0 = 0.456 - 2.64 \cdot 10^{-3} \cdot T_{Fires}$. The dollar value of total losses V_{Fires} from structural fire (in 1993 dollars) is given by $V_{Fires} = 3.443 \cdot (3.845 \cdot 10^3 + 4.31 \cdot 10^2 \cdot T_{Fires})$.

[180] The value for annual fire incidence per capita (0.004 structure fires/capita/year) came from FEMA (2016). As noted elsewhere in this section, we assumed the population affected by extreme temperature and precipitation events equals the county population (i.e., that everyone in the state is equally likely to be impacted by the delays) and that the associated delays are evenly distributed over the average travel hours of the year (12 hours/day multiplied by the number of days in the year. For high tide flooding and storm surge events, the population affected by flooding events — and the fraction of the year during which roads were affected — were calculated as part of the transportation impacts analysis (see Chapters 5.1 and 5.4 of this report for information about traffic delays and affected population, respectively).

[181] The survival probability P_S of a cardiac arrest is given by:

$$P_S = \frac{1}{1 + e^{-0.260 + k_{CPR} \cdot T_{CPR} + k_{Defib} \cdot T_{Defib}}}$$

Where $k_{CPR} = 0.106$, $k_{Defib} = 0.139$, and the time T_{CPR} from collapse to CPR and the time T_{Defib} from collapse to defibrillation depended on EMS response time:

$$T_{CPR} = T_{EMS} + 1$$
$$T_{Defib} = T_{EMS} + 2$$

were affected.[182] The economic impacts of travel delays on EMS response times were calculated as the difference between the impact for the typical EMS response times and the impact taking into account travel delays.

- *Hospitals.* The original FEMA approach calculated the impacts of changes to hospital access as the sum of (1) changes in ambulance travel costs due to travel delays, (2) costs associated with increased waiting time at hospitals, and (3) increased mortality due to travel delays. For this analysis, we adapted the FEMA methodology and focused on changes in mortality due to increased travel time to hospitals for two types of emergencies: (1) myocardial infarctions (i.e., cardiac arrests) and (2) unintentional injuries (i.e., injuries without purposeful intent). The economic impacts from mortality during travel to hospitals depended on changes in mortality during the period that roads were affected. More specifically, the mortality rates from myocardial infarctions and unintentional injuries were calculated as a function of the total travel time to a hospital and the number of myocardial infarction cases and unintentional injuries.[183] The number of myocardial infarctions and the number of unintentional injuries were calculated by multiplying the annual incidence of those cases per capita by the affected population and the fraction of the year during which the roads were affected.[184] Economic impacts of travel delays on access to hospitals were calculated as the difference between the impacts for the typical response time, and the impacts taking into account travel delays.

The data sources used in this analysis are summarized in **Table 7-3**.

---

[182] The value for annual incidence of cardiac arrests per capita ($6.38 \cdot 10^{-4}$ structure cardiac arrests/capita/year) came from FEMA (2016). As noted elsewhere in this section, we assumed the population affected by extreme temperature and precipitation events equals the county population (i.e., that everyone in the state is equally likely to be impacted by the delays) and that the associated delays are evenly distributed over the average travel hours of the year (12 hours/day multiplied by the number of days in the year. For high tide flooding and storm surge events, the population affected by flooding events — and the fraction of the year during which roads were affected — were calculated as part of the transportation impacts analysis (see Chapters 5.1 and 5.4 of this report for information about traffic delays and affected population, respectively).

[183] The economic impacts $I_{Hospitals}$ from mortality during travel to hospitals are given by $I_{Hospitals} = V_{VSL} \cdot (N_{AMI} \cdot M_{AMI} + N_{UI} \cdot M_{UI})$.
Mortality M_{AMI} from cardiac arrests and mortality M_{UI} from unintentional injuries, were calculated as functions of total response time (in minutes):

$$M_{AMI} = k_{AMI} \cdot m_{AMI} \cdot N_{AMI} \cdot \left(\frac{T_{Hospitals} - 0.65}{1.7}\right), M_{UI} = k_{UI} \cdot m_{UI} \cdot N_{UI} \cdot \left(\frac{T_{Hospitals} - 0.65}{1.7}\right)$$

In the calculation of mortality M_{AMI} from cardiac arrests (AMI) and mortality M_{UI} from unintentional injuries (UI):

$k_{AMI} = 6.04 \cdot 10^{-2}$ and $m_{AMI} = 5.07 \cdot 10^{-4}$

$k_{UI} = 6.04 \cdot 10^{-2}$ and $m_{UI} = 5.07 \cdot 10^{-4}$

[184] The value for annual per capita mortality from AMI ($5.09 \cdot 10^{-4}$ deaths from AMI/capita/year) and unintentional injuries ($4.13 \cdot 10^{-4}$ deaths from unintentional injuries/capita/year) came from FEMA (2016). As noted elsewhere in this section, we assumed the population affected by extreme temperature and precipitation events equals the county population (i.e., that everyone in the state is equally likely to be impacted by the delays) and that the associated delays are evenly distributed over the average travel hours of the year (12 hours/day multiplied by the number of days in the year. For high tide flooding and storm surge events, the population affected by flooding events — and the fraction of the year during which roads were affected — were calculated as part of the transportation impacts analysis (see Chapters 5.1 and 5.4 of this report for information about traffic delays and affected population, respectively).

TABLE 7-3. EMERGENCY SERVICES RESPONSE TIMES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Per capita incidence rate of emergencies	National average values, by emergency type	U.S. Federal Emergency Management Agency. 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf
Typical response times	National standard values for typical response times for fire response and EMS	U.S. Federal Emergency Management Agency. 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf
Average travel time to a hospital	Average travel time to a hospital for Mid-Atlantic states	Pew Research Center. 2018. How far Americans live from the closest hospital differs by community type. https://www.pewresearch.org/fact-tank/2018/12/12/how-far-americans-live-from-the-closest-hospital-differs-by-community-type/
Population projections	2010-2100, by county	U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.
Traffic delay data	Average annual traffic delay, total annual event duration, fraction of the population affected, total hourly traffic, by county and type of stressor	See Chapters 5.1 and 5.4.

Results:

Economic impacts of road closures are projected to grow for all emergency service categories from near century to late century. Throughout the century, impacts on hospitals and EMS tend to be at least an order of magnitude larger than impacts on fire services. Extreme temperature and precipitation events have the largest economic impacts at near century and mid-century, with total impacts on emergency services in the millions of dollars. By late century, economic impacts from high tide flooding and storm surge surpass those from extreme temperature and precipitation and storm surge.

Extreme Temperature and Precipitation

Average annual impacts of traffic delays from extreme temperature and precipitation on EMS, fire response, and hospitals are shown in **Table 7-4**. Average annual economic impacts for emergency services are expected to increase for all counties in Delaware throughout the next century. There are two exceptions to this observed trend: annual economic impacts for EMS in New Castle and Sussex Counties decrease from the near century to the mid-century, before increasing in the late century. Both exceptions follow similar decreases to those observed in the underlying data on annual traffic delays, with these differences driven by changes in extreme precipitation events, which have complex, non-linear effects on traffic delays.

Total annual economic impacts for the state overall, as they relate to extreme temperature and precipitation, are greatest for hospital services, followed by EMS services and finally fire services are the smallest. The order-of-magnitude difference in annual impacts between hospital services/EMS and fire services can be explained by observing that hospital services and EMS are both valued using VSL, which has a value about $10 million in $2019. The increase in mortality of a single death per year puts the value of impacts on these two services in the millions. The value of VSL is furthermore adjusted to reflect growth in GDP. In contrast, the valuation of fire response services is not adjusted for GDP growth and increases linearly with the number of fires by about $23,400.[185]

TABLE 7-4. ANNUAL ECONOMIC IMPACTS TO EMERGENCY SERVICES FROM EXTREME TEMPERATURE AND PRECIPITATION ($MILLION)

Economic impacts for EMS are defined as the value of lives lost due to increased mortality; economic impacts for fire services are defined as the total losses (direct property losses, indirect property losses, and the value of mortality and morbidity losses) associated with structure fires; economic impacts for hospitals are defined as the value of lives lost due to increased mortality from myocardial infarctions and unintentional injuries. All impacts are reported in dollars (2019) per year. Impacts are calculated for response times that consider traffic delays due to extreme temperature and precipitation, relative to typical response times for these emergency services. Traffic delays are calculated relative to the baseline period (1986-2005). Results reflect the values for the average annual traffic delays from temperature and precipitation. Values may not sum due to rounding.

Emergency Service Category	County	Near Century (2020-2039)		Mid-Century (2040-2059)		Late-Century (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
EMS	Kent	$0.34	$0.30	$0.52	$0.39	$0.89	$0.56
	New Castle	$3.7	$2.0	$3.2	$2.1	$5.6	$3.5
	Sussex	$1.7	$0.85	$2.4	$1.8	$3.3	$1.6
	Delaware Total	**$5.8**	**$3.2**	**$6.0**	**$4.4**	**$9.8**	**$5.7**
Fire Response	Kent	$0.006	$0.005	$0.009	$0.007	$0.016	$0.010
	New Castle	$0.065	$0.036	$0.056	$0.037	$0.098	$0.063
	Sussex	$0.030	$0.015	$0.042	$0.033	$0.059	$0.028
	Delaware Total	**$0.10**	**$0.056**	**$0.11**	**$0.077**	**$0.17**	**$0.10**
Hospitals	Kent	$0.60	$0.54	$0.93	$0.69	$1.6	$0.99
	New Castle	$6.6	$3.6	$5.6	$3.8	$9.9	$6.3
	Sussex	$3.1	$1.5	$4.2	$3.3	$5.9	$2.8
	Delaware Total	**$10**	**$5.7**	**$11**	**$7.7**	**$17**	**$10**
Total	Kent	$0.94	$0.84	$1.5	$1.1	$2.5	$1.6
	New Castle	$10	$5.7	$8.8	$5.9	$16	$9.9
	Sussex	$4.8	$2.4	$6.6	$5.1	$9.3	$4.4
	Delaware Total	**$16**	**$8.9**	**$17**	**$12**	**$27**	**$16**

High Tide Flooding

Table 7-5 shows average annual impacts of traffic delays from high tide flooding on EMS, fire response, and hospitals. High tide flooding impacts grow substantially throughout the century for all emergency services. Values for Delaware totals grow about nine-fold between near century

---

[185] U.S. Federal Emergency Management Agency (FEMA). 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf. The guidance from this report does not recommend adjustments to the valuation of fire response services over time.

and mid-century. Between mid-century and late century, impacts to fire response grow about 19-fold, those to hospitals grow about 16-fold, and those to EMS grow about 12-fold. The impacts from high tide flooding on hospitals are the largest, followed by impacts on EMS. Impacts from high tide flooding on hospitals and EMS are much lower at near century than impacts from extreme temperature and precipitation but are several-fold larger than impacts from temperature and precipitation by late century. In terms of fire response, annual impacts from high tide flooding are at least an order of magnitude smaller than for hospitals and EMS, for the same reasons explained for the temperature and precipitation results above.

TABLE 7-5. ANNUAL ECONOMIC IMPACTS TO EMERGENCY SERVICES FROM HIGH TIDE FLOODING ($MILLION)

Economic impacts for EMS are defined as the value of lives lost due to increased mortality; economic impacts for fire services are defined as the total losses (direct property losses, indirect property losses, and the value of mortality and morbidity losses) associated with structure fires; economic impacts for hospitals are defined as the value of lives lost due to increased mortality from myocardial infarctions and unintentional injuries. All impacts are reported in dollars (2019) per year. Impacts are calculated for response times that consider traffic delays due to high tide flooding on roadways (relative to a no-SLR baseline year of 2000), relative to typical response times for these emergency services, as modeled in the National Coastal Property Model. Values may not sum due to rounding.

Emergency Service Category	County	Near Century (2020-2039)	Mid-Century (2040-2059)	Late-Century (2080-2099)
EMS	Kent	$0.089	$0.50	$4.6
	New Castle	$0.039	$0.81	$13
	Sussex	$0.065	$0.37	$1.9
	Delaware Total	**$0.19**	**$1.7**	**$20**
Fire Response	Kent	$0.002	$0.011	$0.12
	New Castle	$0.001	$0.015	$0.43
	Sussex	$0.001	$0.008	$0.11
	Delaware Total	**$0.004**	**$0.035**	**$0.66**
Hospitals	Kent	$0.2	$1.2	$13.0
	New Castle	$0.1	$2	$39
	Sussex	$0.12	$0.8	$6
	Delaware Total	**$0.4**	**$4**	**$57**
Total	Kent	$0.27	$1.7	$17.0
	New Castle	$0.11	$2.4	$53
	Sussex	$0.19	$1.2	$7.5
	Delaware Total	**$0.58**	**$5.2**	**$77**

Sea Level Rise and Storm Surge

Table 7-6 shows the average annual impacts of traffic delays from SLR and storm surge on EMS, fire response, and hospitals. Economic impacts of SLR and storm surge are largest on hospitals and EMS and lowest for fire response. At near century, impacts from SLR and storm surge are like those from high tide flooding for all sectors.

TABLE 7-6. ECONOMIC IMPACTS OF STORM SURGE EVENTS TO EMERGENCY SERVICES ($MILLION)

Economic impacts for EMS are defined as the value of lives lost due to increased mortality; economic impacts for fire services are defined as the total losses (direct property losses, indirect property losses, and the value of mortality and morbidity losses) associated with structure fires; economic impacts for hospitals are defined as the value of lives lost due to increased mortality from myocardial infarctions and unintentional injuries. All impacts are reported in dollars (2019) per year. Impacts are the result of traffic delays due to flooding from 1-percent and 10-percent storm surge events, measured in dollars (2019). Traffic delays are calculated relative to the no-SLR baseline (year 2000). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The values below represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year). Values may not sum due to rounding.

Emergency Service Category	County	Near Century (2020-2039)		Mid-Century (2040-2059)		Late-Century (2080-2099)	
		10% storm	1% storm	10% storm	1% storm	10% storm	1% storm
EMS	Kent	$0.037	$0.053	$0.066	$0.085	$0.14	$0.037
	New Castle	$0.044	$0.17	$0.21	$0.48	$0.88	$0.044
	Sussex	$0.071	$0.17	$0.10	$0.24	$0.20	$0.071
	Delaware Total	**$0.15**	**$0.39**	**$0.38**	**$0.80**	**$1.2**	**$0.15**
Fire Response	Kent	$0.001	$0.001	$0.002	$0.002	$0.004	$0.001
	New Castle	$0.001	$0.003	$0.004	$0.013	$0.044	$0.001
	Sussex	$0.002	$0.006	$0.005	$0.016	$0.015	$0.002
	Delaware Total	**$0.004**	**$0.010**	**$0.011**	**$0.031**	**$0.063**	**$0.004**
Hospitals	Kent	$0.083	$0.12	$0.15	$0.22	$0.41	$0.083
	New Castle	$0.081	$0.33	$0.44	$1.3	$2.2	$0.081
	Sussex	$0.23	$0.58	$0.31	$0.69	$0.58	$0.23
	Delaware Total	**$0.39**	**$1.00**	**$0.91**	**$2.2**	**$3.2**	**$0.39**
Total	Kent	$0.12	$0.17	$0.22	$0.30	$0.56	$0.12
	New Castle	$0.13	$0.50	$0.66	$1.8	$3.1	$0.13
	Sussex	$0.30	$0.76	$0.42	$1.0	$0.80	$0.30
	Delaware Total	**$0.55**	**$1.4**	**$1.3**	**$3.0**	**$4.5**	**$0.55**

Limitations:

- We are unaware of any Delaware-specific values for incidence rates of emergencies underlying the estimation of impacts on emergency services. As a result, we use standard values for these incidence rates, as suggested by FEMA in their benefit-cost methodology for estimating the value of emergency services. Some of these values were calculated from data from the early 21st century. These values may not account for changing trends in incident rates or local patterns.[186] The uncertainties introduced by national values instead of Delaware-specific values are unknown.

---

[186] FEMA. 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

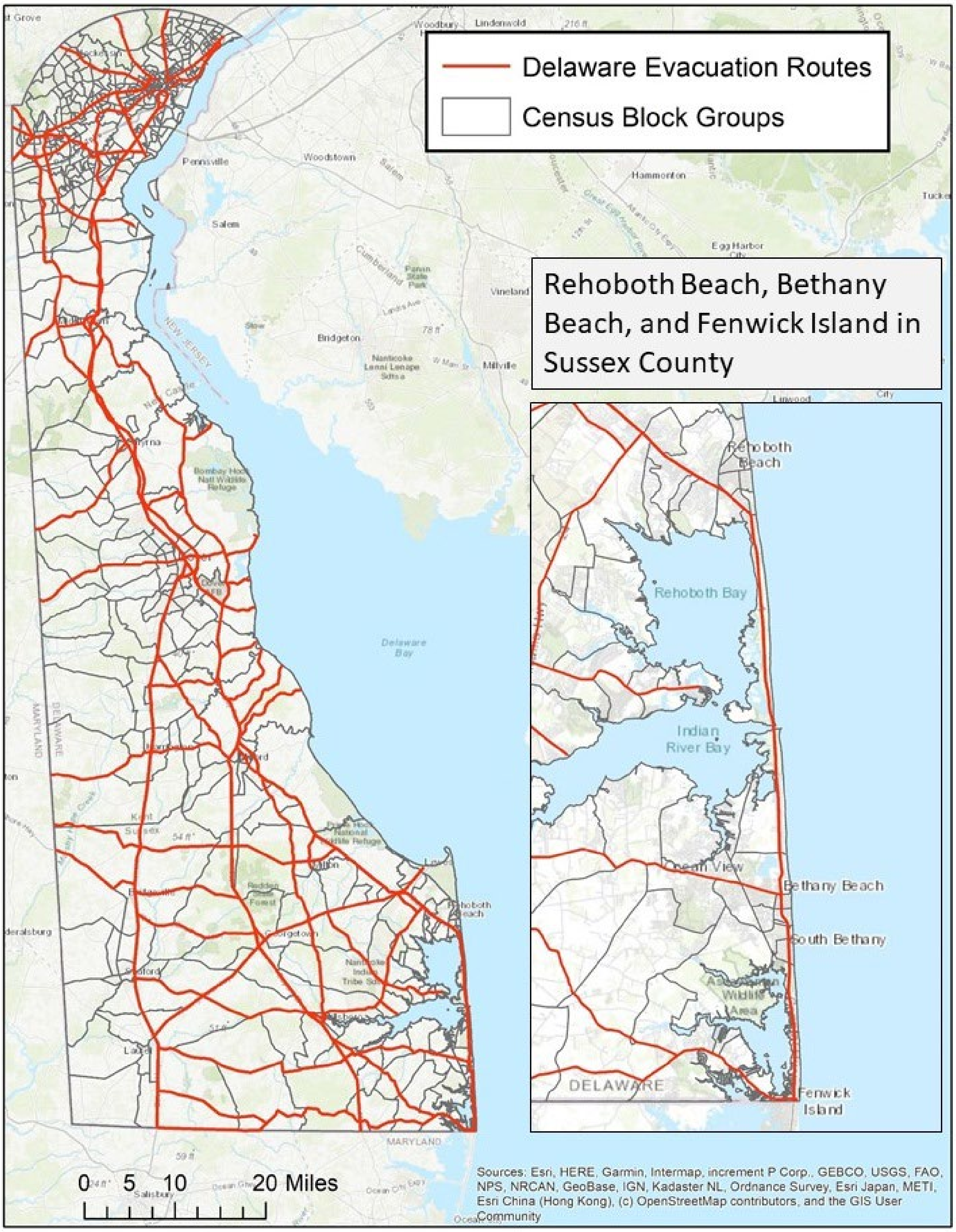
- The estimation of these economic impacts did not account for the potential increase in incidence rates during extreme weather or climate change. The uncertainties introduced by these values are unknown.
- This analysis relied on values produced for the analysis of transportation impacts described in Chapters 5.1 and 5.4. The limitations described in those sections also apply here.

7.2 ACCESS AND UPKEEP OF EVACUATION ROUTES

Access and upkeep of evacuation routes in terms of mortality risk of coastal flooding events

DelDOT is responsible for maintaining evacuation routes, which are essential for public safety during emergencies, including natural disasters. **Figure 7-2** shows evacuation routes statewide and the inset highlights the routes critical to storm surge hazard evacuation along the Atlantic coast of Sussex County. In this analysis, we explore the importance of evacuation routes for coastal populations potentially affected by storm surge flooding.

FIGURE 7-2. DELDOT EVACUATION ROUTES AND CENSUS BLOCK GROUP BOUNDARIES



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Methods:

We calculate the mortality risk of storm surge flooding by identifying the exposed population, calculating flood depths by storm surge event and exposed population, and applying a flood mortality function from Boyd (2005).[187] In this analysis, we do not adjust for the likelihood of populations to evacuate prior to storm surge events.

The data sources used in this analysis are summarized in **Table 7-7**.

TABLE 7-7. ACCESS AND UPKEEP OF EVACUATION ROUTES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Population	Baseline, by block group	American Community Survey 2018. https://www.census.gov/programs-surveys/acs
	Future, by county. Used to scale up baseline block group by county	U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.
Willingness to pay to avoid mortality risk (VSL)	For 2030, 2050, and 2090, scales with projected Gross Domestic Product per capita	U.S. EPA. 2018. Documentation for the BenMAP air pollution benefits estimation tool.
Mortality function	Percent mortality of exposed population by flood depth (m)	Boyd. E. 2005. Toward an empirical measure of disaster vulnerability: storm surges, New Orleans, and Hurricane Betsy. Poster presented at the 4th UCLA conference on public health and disasters, Los Angeles, 1-4 May 2005.

First, we use the National Coastal Property Model to identify the upland property area inundated at 0.25 ft-increments of storm surge heights, up to six feet. We identify the proportion of the population affected at each height by spatially distributing Census block group populations[188] to match the distribution of property value over the same area (stored within the National Coastal Property Model and adjusted to publicly available Zillow value estimates from 2017) and summing over each inundation layer and county. We apply the percentage of affected population to the Integrated Climate and Land Use Scenarios version 2 projected county populations to obtain the total population affected. The result of this process is a count of inundated population by county at 24 storm surge increments from zero to six feet (see columns C and D of **Table 7-8**).

Next, we calculate the flood depths experienced for each affected population at each storm surge height (see column E of **Table 7-8**). Storm surge heights by era and county are described further in Chapter 2. In the absence of detailed elevation and flow modeling data, we estimate flood depth as the storm surge height minus the elevation at which the population in that area first experienced flooding. For example, at 2.0 feet of storm surge, a population that was first flooded at 0.5 feet would experience a flood depth of 1.5 feet; a second location that is first flooded at 1.0 feet would experience a flood depth of 1.0 feet.

Boyd (2005) defines a flood fatality function based on observed fatality rates and water depths for 20 locations from seven historical flood events. Boyd estimates that mortality rates begin to increase rapidly around three meters, or ten feet, of flooding, which falls above the highest

---

[187] Boyd E (2005) Toward an empirical measure of disaster vulnerability: storm surges, New Orleans, and Hurricane Betsy. Poster presented at the 4th UCLA conference on public health and disasters, Los Angeles, 1-4 May 2005

[188] ACS 2018 5-year data estimates. There are 574 block groups in Delaware with an average population of about 1,500 people.

expected storm surge depths in Delaware over the century. Nevertheless, given the value of increased mortality risk, even small changes in risk can have large economic consequences. We convert flood depths at each county and storm surge event to meters and calculate percent mortality using the function presented in Boyd (2005) (see columns F and G of **Table 7-7**).

Finally, we calculate the total mortality risk associated with the event by multiplying the calculated mortality rates by the exposed populations at each flood depth and storm event and summing across all flood depths for each storm event and county (see column H of **Table 7-8**). Note that mortality from flooding has been documented for coastal storms in Delaware, but not every storm produces mortality. While deaths can only occur in whole units, mortality risk, measured in units of statistical deaths, is frequently reported in fractions of statistical deaths, as we illustrate in **Table 7-8** below. Mortality risk is valued using the VSL as defined in Chapter 2.

For each storm event, we then sum the total event mortality risk for each increment of flood height. **Table 7-8** illustrates the various steps of this analysis using an example case of the Sussex County 1-percent storm event.

TABLE 7-8. EXAMPLE CALCULATION FOR LATE CENTURY SUSSEX COUNTY, 1-PERCENT STORM

SEA LEVEL HEIGHT (FT)[a]	EXPOSED POPULATION			MORTALITY RATE			TOTAL EVENT MORTALITY RISK
	PERCENT OF POPULATION INUNDATED[b]	TOTAL EXPOSED POPULATION (2090)	INCREMENTAL EXPOSED POPULATION	FLOOD DEPTH (FT) FROM 1% STORM (8.9FT)	FLOOD DEPTH (M)	MORTALITY RATE[c]	
[A]	[B]	[C]=[B] X 186,652	[D]= [C] - [C_{N-1}]	[E] = 8.9 - [A]	[F]= [E]/3.28	[G]= FN([F])	[H]= [D] X [G]
0.25	0.0%	0	0	8.65	2.64	0.56897%	0.00
0.50	0.0%	0	0	8.40	2.56	0.35753%	0.00
0.75	0.0%	0	0	8.15	2.48	0.22414%	0.00
1.00	0.0%	0	0	7.90	2.41	0.14030%	0.00
1.25	0.0%	11	11	7.65	2.33	0.08775%	0.01
1.50	0.0%	69	58	7.40	2.26	0.05484%	0.03
1.75	0.1%	169	100	7.15	2.18	0.03427%	0.03
2.00	0.2%	330	161	6.90	2.10	0.02141%	0.03
2.25	0.3%	639	309	6.65	2.03	0.01337%	0.04
2.50	0.5%	1,020	381	6.40	1.95	0.00835%	0.03
2.75	0.8%	1,403	383	6.15	1.87	0.00521%	0.02
3.00	0.9%	1,735	332	5.90	1.80	0.00326%	0.01
3.25	1.1%	2,076	341	5.65	1.72	0.00203%	0.01
3.50	1.3%	2,440	364	5.40	1.65	0.00127%	0.00
...							...
6.00	3.7%	6,981	621	2.90	0.88	0.00001%	0.00
						Total Event Mortality Risk	**0.23**

Note:
a. Sea level heights between 3.5 and 6 feet are truncated to conserve space; the majority of mortality risk occurs under 3.5 feet.
b. Values from the National Coastal Property Model.
c. See Boyd 2008.

Results:

Mortality risk is projected to remain relatively low in Delaware based on calculated flood depths for most of the storm surge events. The one exception is the late century 1-percent storm event in

Sussex County. As seen in **Table 7-9**, the majority of the risk for this event is borne by populations falling in the 1.5 to 2.5foot storm surge inundation area (about 0.8% of the county population, or 1,400 people).

TABLE 7-9. ECONOMIC IMPACTS OF STORM SURGE EVENTS TO ACCESS AND UPKEEP OF EVACUATION ROUTES

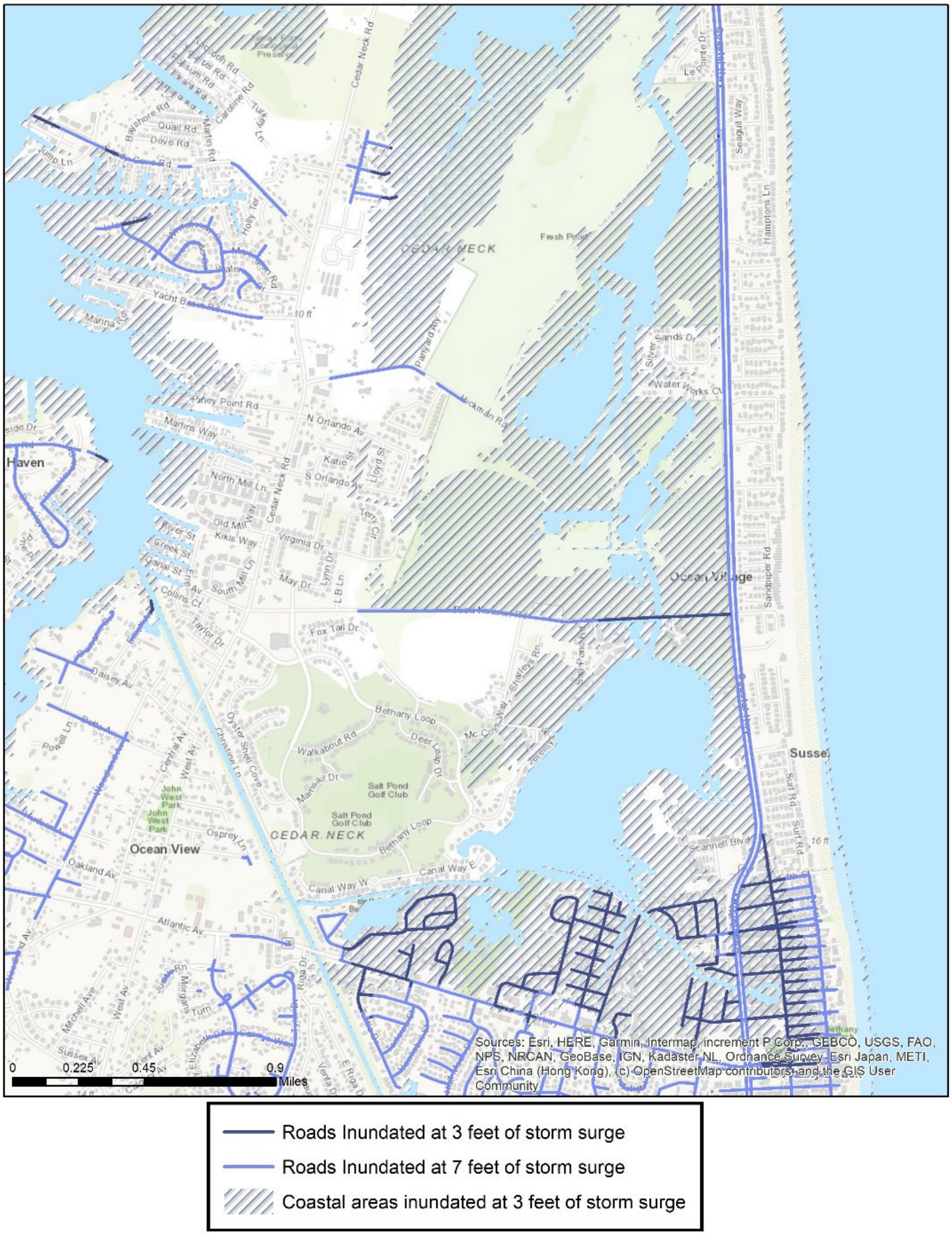
Economic impacts defined as willingness to pay to avoid added mortality risk (VSL) resulting from 1-percent and 10-percent storm surge events, measured in dollars (2019). The results are based on NOAA (2019) storm surge heights and are calculated using the intensity levels of such storm surge events under current climate conditions, above projected SLR in each era. The values below represent the full impact of an event of this magnitude occurring in the subject year (i.e., results are not adjusted to reflect the probability of the event occurring in a given year). Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
	10% storm	1% storm	10% storm	1% storm	10% storm	1% storm
Kent County	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000	<$1,000
New Castle County	<$1,000	<$1,000	<$1,000	$4,200	$14,000	$89,000
Sussex County	<$1,000	$38,000	$2,200	$170,000	$45,000	$3,600,000
Delaware Total	**<$1,000**	**$39,000**	**$2,900**	**$180,000**	**$60,000**	**$3,600,000**

These results highlight the need for maintaining evacuation routes that enable potentially exposed populations to avoid exposure to dangerous flooding events, assuming people continue living in the affected areas. **Figure 7-4** shows a portion of coastal Sussex County that is particularly vulnerable to flooding events due to limited evacuation routes. Maintaining evacuation routes and implementing early warning systems may alleviate mortality risk in this area.

FIGURE 7-4. INUNDATED AREAS BETWEEN BETHANY BEACH AND DEWEY BEACH (SUSSEX COUNTY) AT 3 AND 7 FEET OF STORM SURGE

Flooded roads highlighted in dark purple (3 foot sea level elevation) and light purple (7 foot sea level elevation). Storm surge in Sussex County is projected to 6.6 feet for the 10-percent storm and 8.9 feet for the 1-percent storm by late century.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Limitations:

- Flood depths are modeled using a simplified approach that does not capture the nuances in elevation that affect flooding at a localized level. In addition, the analysis does not directly consider the site-specific health risks from potentially increased wave velocities or debris flow associated with storm surge. Instead, the Boyd (2005) meta-analysis implicitly considers mortality risk from these sources, as reflected by stillwater flood depth.
- In this analysis, populations are distributed across area by Census block groups based on the spatial distribution of property value. Population and property value, however, do not necessarily correlate closely, for example in areas with densely populated areas of many small, lower-value properties, and in areas with large, high-value, single-family properties. A finer spatial distribution of population (i.e., Census blocks) could potentially provide more precise spatial population distributions. However, such finer spatial distribution may actually create a false precision, given the coarser resolution of our estimation of flood areas and the inability to consider detailed, site-specific flood risks in this analysis.
- In determining vulnerable populations, we assume no evacuation prior to storm events. The mortality rates calculated using Boyd (2005), apply to the in-place population and therefore evacuations would result in, at minimum, a proportional reduction in mortality. If populations at risk of higher flood depths evacuate at higher rates than those in lower flooding areas, evacuation could have a stronger impact on mortality risk.
- Similar to the above note, we also assume that populations continue to live in these affected areas as part of the “status quo” control scenario. Adaptation actions, such as managed retreat, would reduce the exposed population and therefore reduce mortality outcomes.

7.3 FREQUENCY OF EMERGENCY RESPONSES

Frequency of emergency responses due to increased flooding and storms

Flood and storm events could reasonably be anticipated to increase the risk of injuries and disease both during and after an event. Injuries or acute morbidity may be associated with flooding itself, actions taken to evacuate, individual responses to the loss of shelter, disruptions to utilities such as electric power, or the loss of safe drinking water sources. Some of these injuries or acute medical conditions may be severe enough to require emergency department visits, hospital admissions, and/or emergency responses from trained medical personnel. In this section we assess available information on potential changes in frequency of emergency responses due to increased flooding and storms, and the cost to provide increased emergency responses, relative to periods where no storm or flooding has occurred.

Methods:

We are not aware of any peer-reviewed, published quantitative analysis that provides a basis for reliably projecting changes in the need for emergency response during flooding and storms. In addition, no specific information for Delaware is available to show higher rates of emergency response during storms and flooding events. As these events are relatively infrequent, discerning differences in the relevant emergency response rates requires a careful and systematic experimental design, coupled with precise, time-bound data on response actions.

The topic of health effects associated with storm and flood events, however, has been a subject of study in Florida since 2015. Jagger et al. (2015)[189] provide data and systematic methods to estimate these effects while Kintziger et al. (2017)[190] present a systematic literature review. These documents provide methodologies, data sources, and conceptual links between storms and health effects. Many of these health effects may require emergency response, but the documents do not include application of these methods. One such careful application has been conducted for flooding and storm events in Florida, but is available only in the form of a conference presentation (Kintziger et al. 2019).[191] This application compares daily counts of selected health outcomes for the impact period (consisting of the day(s) of the event plus an additional set of follow-up days, totaling 14 days overall) to two matching 14 day control periods before and after the impact period. Two types of impacts, or extreme events, were assessed: a broad measure of severe flood, wind, or other storm events (called “all impacts”); and named hurricanes. Using conditional Poisson regression models, the Kintziger et al. (2019) approach yields results in the

---

[189] Jagger MA, Kintziger KW, Dumas JS, Watkins S. March 2015. Health Effects of Tropical Storms and Hurricanes in Florida. Tallahassee, FL, Florida Department of Health. Available at http://www.floridahealth.gov/environmental-health/climate-and-health/_documents/tc-profile.pdf .

[190] Kristina W. Kintziger, Meredith A. Jagger, Kathryn C. Conlon, Kathleen F. Bush, Brendon Haggerty, Laurel Harduar Morano, Kathryn Lane, Matthew Roach, Lauren Thie, Christopher K. Uejio. 2017. Technical Documentation on Exposure-Response Functions for Climate-Sensitive Health Outcomes. Centers for Disease Control and Prevention Climate and Health Program Technical Documentation Series, 2017.Available at https://www.cdc.gov/climateandhealth/docs/ExposureResponseFunctions_508.pdf .

[191] Kristina W. Kintziger, Evah W. Odoi, Meredith A. Jagger. 2019. Impacts of Climate Change & Extreme Weather on Injury: A Primer for Investigation Focusing on Hurricane-Related Impacts. Presented at the January 8, 2019 annual meeting of the American Meteorological Association, as part of Themed Joint Session 15 – Hurricanes and Health: When Will We Stop “Learning Lessons” and Start Building Smarter? Abstract and recorded presentation available at: https://ams.confex.com/ams/2019Annual/webprogram/Paper354540.html; presentation text obtained from the authors.

form of relative risks (i.e., ratios of risks in the impact period compared to the control period) and 95 percent confidence intervals around the mean relative risk.

The study assessed four classes of health effects: drownings; injuries; carbon monoxide poisonings; and food and waterborne diseases. The most robust results are for injuries and carbon monoxide poisonings, with statistically significant results (i.e., 95 percent confidence intervals that establish relative risk results greater than a ratio of one) for both the "all impacts" and hurricane impacts. While injuries are a direct consequence of the weather event, carbon monoxide poisonings result from an indirect pathway. Weather and hurricane events cause power outages, which leads to increased use of gasoline and diesel-powered generators. The emissions from gasoline and diesel-powered generators contain high levels of carbon monoxide, which can infiltrate living areas if not properly vented.

From the study, we use a best estimate relative risk result of 1.04 for injuries associated with "all impacts" and 1.24 for injuries associated with hurricane events.[192] We also use a best estimate relative risk of 6.59 for the broadest measure of carbon monoxide poisonings (measured as a call to the Florida poison control center for carbon monoxide poisoning) associated with "all impacts" and 14.94 for hurricane events.

To measure the incremental number of emergency response calls, we estimate the average baseline (control period) incidence of injuries and carbon monoxide poisonings in Delaware over a typical two-week period, and then apply the relative risk estimates to generate excess risks during storm events. For carbon monoxide poisonings, data are sparse, but an online article states that, across the U.S. in 2018, there were approximately 15,000 emergency department visits for non-fire-related carbon monoxide poisoning; additionally, the article notes that, over the 1999-2012 period, there were 438 deaths per year due to non-fire-related carbon monoxide poisoning.[193] If we adjust the national estimates for Delaware's population share in 2018, we estimate approximately 45 cases per year in Delaware, and approximately 2 cases per two-week period. For injuries, the estimated baseline annual injuries during a two-week period in Delaware is approximately 3,300 and was established based on national data on unintentional injuries for 2017.[194]

We also estimated the change in frequency of hurricanes and other storms in Delaware that can be attributed to climate change, although these data are not used in the results reported below for the 100-year hurricane event. For hurricanes, the change in frequency of the current 1-percent hurricane event, by county, based on analysis in Marsooli et al. (2019) is estimated to be an increase to a 10 percent annual frequency by early-century, and an increase to 50 percent annual

---

[192] The "best estimate" referred to in the text is the mean estimate from a conditional Poisson regression estimation. The 95% confidence interval is not necessarily symmetric and generally tends to skew with a longer tail to the right, extreme high values.

[193] See Medscape online article, by Guy N Shochat, MD, updated December 30, 2020, What is the incidence of carbon monoxide (CO) toxicity in the U.S.? Available at: https://www.medscape.com/answers/819987-70262/what-is-the-incidenc

[194] National Center for Health Statistics, FastStats Homepage on Accidents or Unintentional Injuries. Per capita national rate estimated using total emergency department visits for unintentional injuries in 2017 of 29.4 million, divided by 2017 U.S. population of 325.1 million. Available at: https://www.cdc.gov/nchs/fastats/accidental-injury.htm

frequency by mid-century, and an increase to 100 percent annual frequency by end century.[195] The estimates reported are the cost of injury and carbon monoxide poisonings for a single current 1-percent storm, but as Marsooli et al. indicate, the frequency of that event could increase substantially in the future as a result of climate change.[196] For storms other than hurricanes, we use estimates of the statewide change in frequency of the 24-hour 2-inch total precipitation rainstorm event derived from the Delaware Climate Change Impact Assessment.[197]

Valuation of the cost of an emergency response call is based on the sum of employee wages for two Emergency Medical Technicians, for an average response time of 13.3 minutes, plus travel costs. The method is based on estimates developed for FEMA and described in more detail in Chapter 7.1 on emergency response and traffic delays. The total cost per response is estimated at $40.62.[198] Note that because health impacts are not part of the stated scope of this sector, and to avoid double counting economic impacts with the evacuation analysis discussed in Chapter 7.2, the valuation of emergency response includes only the cost of the emergency response call (staff and equipment costs), and not the incremental cost of medical treatment or the possibility of deaths associated with these effects. Note that the Chapter 7.2 evacuation analysis considers the potential for flood risk to lead to mortality if individuals are unable to evacuate. The data sources used in this analysis are summarized in **Table 7-10**.

---

[195] The Marsooli et al. study provides an event-based estimate of the frequency of a 1 percent hurricane storm surge event, which is suitable for this analysis, but because the results are limited to the 1 percent event, and to a single time period (late century), we do not use Marsooli et al. in other storm surge flood depth analyses in this report, only for event frequency analyses. Note that unlike other storm surge analyses, the event-based frequency estimate allows us to generate a scalar for hurricane frequency that is applied to the baseline risk, resulting in an annual estimate of disease incidence for future periods. Other analyses rely on flood mapping of storm surge and which at this time cannot be adjusted for the full range of flood events across all return periods (that is, for other than the 1 percent storm).

[196] Marsooli, R., Lin, N., Emanuel, K., and Feng, K., 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. *Nature Communications*. 10:3785, DOI:10.1038/s41467-019-11755-z.

[197] February 2014 – see Table 4.1, page 4-25.

[198] See U.S. Federal Emergency Management Agency (FEMA). 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

TABLE 7-10. FREQUENCY OF EMERGENCY RESPONSES ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Estimated relative risk of injuries and carbon monoxide poisonings associated with weather events	Matched ecological study of the impact of impact of weather events on selected health effects during a 14 period following a weather event, compared to incidence during control periods	Kintziger, K.W., Odoi, E.W. and Jagger, M.A. 2019. Impacts of Climate Change & Extreme Weather on Injury: A Primer for Investigation Focusing on Hurricane-Related Impacts. Presented at the January 8, 2019 annual meeting of the American Meteorological Association. https://ams.confex.com/ams/2019 Annual/webprogram/Paper354540.html
Carbon monoxide poisoning baseline incidence	Online national data and IEc calculations to scale to Delaware by population share	Shochat, G.N. (MD). 2020. What is the incidence of carbon monoxide (CO) toxicity in the U.S.? https://www.medscape.com/answers/819987-70262/what-is-the-incidenc
Injury baseline incidence	Based on national data for emergency department visits for unintentional injuries, scaled to Delaware by population share	Information on unintentional injuries from the Centre for Disease Control. https://www.cdc.gov/nchs/fastats/accidental-injury.htm
Hurricane frequency, 1-percent storm event	Change in frequency of the 1-percent hurricane event in each Delaware county	Marsooli, R., Lin, N., Emanuel, K. and Feng, K. 2019. Climate change exacerbates hurricane flood hazards along U.S. Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications. 10, 3785.
Change in frequency of 24-hour 2-inch precipitation event	Statewide estimate from prior work sponsored by DNREC	Delaware Climate Change Impact Assessment. 2014.
Cost of emergency response call	Estimate of resource cost of an emergency response call, including both labor and equipment costs	Based on FEMA methodology, described in more detail in Chapter 7.1.

Results:

The economic impact results shown in **Table 7-11** are small relative to other categories of public safety effects attributed to climate change. When emergency response frequency scales up with climate change, injury-related impacts are larger overall than carbon monoxide poisoning impacts (even though carbon monoxide poisonings increase faster with climate change). This is in part because the baseline incidence of injuries is much larger than for carbon monoxide poisonings. Impacts for all counties are estimated to grow very slowly through the projection period.

TABLE 7-11. ANNUAL ECONOMIC IMPACTS FROM INCREASED FREQUENCY OF EMERGENCY RESPONSE DUE TO EXTREME PRECIPITATION

Economic impacts defined as the cost of additional emergency response calls associated with storm incidence, as indicated by the frequency of a 24-hour 2-inch rainfall event in future periods relative to the 1981-2010 baseline period. Impacts are measured in dollars (2019) and averaged over GCMs assessed in DNREC (2014). Values may not sum due to rounding.

		NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE CENTURY (2080-2099)	
		RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Carbon monoxide Poisonings	Kent County	$100	$100	$110	$100	$130	$110
	New Castle County	$280	$280	$310	$280	$390	$310
	Sussex County	$100	$100	$110	$100	$140	$110
	Delaware Total	**$480**	**$480**	**$520**	**$480**	**$660**	**$520**
Injuries	Kent County	$1,300	$1,300	$1,400	$1,300	$1,800	$1,400
	New Castle County	$3,700	$3,700	$4,000	$3,700	$5,100	$4,000
	Sussex County	$1,300	$1,300	$1,400	$1,300	$1,800	$1,400
	Delaware Total	**$6,400**	**$6,400**	**$6,900**	**$6,400**	**$8,600**	**$6,900**
Total	Kent County	$1,400	$1,400	$1,500	$1,400	$1,900	$1,500
	New Castle County	$4,000	$4,000	$4,400	$4,000	$5,500	$4,400
	Sussex County	$1,400	$1,400	$1,500	$1,400	$1,900	$1,500
	Delaware Total	**$6,800**	**$6,800**	**$7,400**	**$6,800**	**$9,300**	**$7,400**

As noted above, our estimate of economic impacts from changes in frequency of emergency response during hurricanes was only performed for the 1-percent hurricane. The results shown in **Table 7-12** show a rapid increase in the risk of a 1-percent hurricane making landfall in Delaware, which could lead to much larger impacts on emergency response services over time, with climate change.

TABLE 7-12. ECONOMIC IMPACTS FROM INCREASED FREQUENCY OF EMERGENCY RESPONSE DUE TO THE 1% HURRICANE EVENT

Economic impacts are defined as the cost of additional emergency response calls associated with a 1-percent hurricane frequency, based on the intensity of such a storm under current climate conditions, measured in dollars (2019) per year. Values may not sum due to rounding. The results presented here are for illustrative purposes only.

		NEAR CENTURY (2020-2039) 1% hurricane	MID-CENTURY (2040-2059) 1% hurricane	LATE CENTURY (2080-2099) 1% hurricane
Carbon monoxide Poisonings	Kent County	<$1,000	<$1,000	<$1,000
	New Castle County	<$1,000	<$1,000	<$1,000
	Sussex County	<$1,000	<$1,000	<$1,000
	Delaware Total	$1,100	$1,100	$1,100
Injuries	Kent County	$6,500	$6,500	$6,500
	New Castle County	$19,000	$19,000	$19,000
	Sussex County	$6,700	$6,700	$6,700
	Delaware Total	$32,000	$32,000	$32,000
Total	Kent County	$6,700	$6,700	$6,700
	New Castle County	$19,500	$19,500	$19,500
	Sussex County	$6,900	$6,900	$6,900
	Delaware Total	**$33,000**	**$33,000**	**$33,000**

Limitations:

- Estimates for changes in carbon monoxide poisonings and injuries are obtained from an unpublished study. While the results follow an established, published method, they have not undergone peer review. Additionally, the study (Kintziger et al. 2019) estimates health effects associated with extreme weather events, rather than emergency responses specifically. While we believe that the method is well documented and that we have reasonably applied the health effect-specific results to estimate changes in demand for emergency services — for example, we excluded effects on food- and water-borne diseases reported in the study, because they have insufficient statistical support — the lack of peer review and the lack of specific focus on emergency calls may have some uncertain effect on our results.
- Baseline incidence rates for carbon monoxide poisoning and injuries, and by extension for the emergency response outcome that we estimate, are based on national data scaled

to Delaware. The actual baseline incidence may be higher or lower than national data indicate.

- Our estimates of the cost of emergency response calls are based on national averages for incidence rates and travel distance and do not take into account the possibility that response times could be much longer during extreme events (which can, in turn, increase the risk of more severe health impacts, including death). In addition, we omit the incremental cost of health impacts and the potential for mortality risk associated with carbon monoxide poisonings. All of these assumptions lead to a likely underestimation of the economic impact, but better data on the true cost of emergency response calls is not currently available.

7.4 LIMITED ACCESS TO COOLING FOR VULNERABLE POPULATIONS

Limited access to cooling for vulnerable populations during extreme temperatures and heat waves

High-temperature days and exposure to extreme heat can impact human health. As described in Chapter 4.1 of this document, high temperatures can reduce the body's ability to regulate internal temperatures, and, in the most extreme cases, can lead to death. Access to cooling centers has been shown to dramatically reduce extreme temperature mortality but use of cooling centers during high-temperature days can be limited by lack of availability, unwillingness of vulnerable populations to use the centers, or inability to access these resources in a timely manner.

Methods:

As described in Chapter 4.1, we estimated overall heat-related mortality based on an application of a study on heat stress and mortality (Mills et al. 2014), which was subsequently modified and expanded by the U.S. EPA (2017).[199] That work did not include any cities in Delaware; however, we pooled results from three cities closest to Delaware that share similar latitude and geography: Washington, D.C., Baltimore, and Philadelphia. The estimated mortality effects are limited to urban populations and therefore were limited in application to only the largest city in each county in Delaware (Dover, Wilmington, and Seaford). The valuation of mortality risk associated with heat stress adopts a standard VSL approach. Here we use the U.S. EPA VSL values used in U.S. EPA (2017), with the methods further documented in U.S. EPA (2018).[200]

The estimates provided in Chapter 4.1 reflect the risk of premature mortality from heat stress that are consistent with the baseline conditions for access to cooling centers in Delaware. To our knowledge, access to cooling centers is not currently tracked as a measure of vulnerability to this health risk. A population's access to cooling centers is, in fact, difficult to measure precisely. The impact of limited access on individual mortality risk from heat stress, however, has been assessed by several studies, which are summarized in a 2018 U.S. Center for Disease Control report on the efficacy of cooling centers in mitigating extreme heat risk.[201] The Center for Disease Control report defines a cooling center or shelter as "…a location, typically an air-conditioned or cooled building that has been designated as a site to provide respite and safety during extreme heat. This may be a government-owned building such as a library or school, an existing community center, religious center, recreation center, or a private business such as a coffee shop, shopping mall, or movie theatre."

One of the earliest and best known case studies on the impact of early warning systems, a measure which can facilitate individuals' propensity to access cooling centers, developed a

---

[199] Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, M. Duckworth, and L. Deck, 2014: Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. *Climatic Change*, doi: 10.1007/s10584-014-1154-8, as extended by EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001, Chapter 5, Extreme Temperature Mortality.

[200] EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001, Chapter 5, Extreme Heat Mortality. U.S. EPA 2018, Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CD) User's Manual, see page H-4. Document available here: https://www.epa.gov/sites/production/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

[201] Widerynski, S., Schramm, P.J., Conlon, K.C., Noe, R.S., Grossman, E., Hawkins, M., Nayak, S.U., Roach, M. and Hilts, A.S., 1917. Use of cooling centers to prevent heat-related illness: summary of evidence and strategies for implementation. Available at https://www.cdc.gov/climateandhealth/docs/UseOfCoolingCenters.pdf

benefit-cost assessment of early warning systems for Philadelphia (Ebi et al. 2004).[202] The Ebi et al. work, coupled with five other studies that provide either specific estimates or "weight-of-evidence" support for this category of effect, form the basis for estimating the marginal effect of access to cooling centers on extreme heat mortality risk for this analysis:

- Bouchama et al. (2007) conducted a rigorous meta-analysis of six studies (four U.S. and two European), the result of which indicates that visiting cool environments reduces extreme heat mortality by 66 percent (95 percent confidence interval of 50 to 80 percent). This meta-analysis estimates the difference in heat mortality outcomes among the general population exposed to extreme heat, a portion of which visited a cooling center during a heat event, by statistical analysis of actual mortality outcomes. The aggregate number of observations across the six studies was approximately 2,500, of which about 1,100 were case patients exposed to heat and 1,400 were control patients. Statistical tests showed no difference in the effect for U.S. and European settings. The four U.S. study settings were in midwestern cities (Chicago, Cincinnati, St. Louis, and Kansas City).[203]
- Vandentorren et al. (2006) found that cooling techniques and devices were protective factors against extreme heat mortality in the August 2003 heat wave in France. Among the relatively small number of subjects who "visited cooler places" mortality was reduced by roughly 50 percent (95% confidence interval of 0 to 71%).[204]
- Palecki et al. (2001) attributed the 80 percent lower mortality in the 1999 Chicago heat wave, relative to the 1995 Chicago heat wave, to heat warning systems, cooling centers, and increased attendance at air-conditioned shopping malls and theaters during the heat wave.[205]
- Ebi et al. (2004) estimated that a heat early warning system implemented in Philadelphia had an estimated effect of saving 2.6 lives per day of heat wave, though with wide error bounds – they concluded that there was a 92 percent chance that the system saved at least one life. A key result was that the benefits of the system likely far outweighed the costs. The main results are based on empirical analysis of mortality incidence during heat waves. It is likely that at least some individuals responded to the warnings by taking shelter in a cooled space, but data were not available on individual behaviors, so the study cannot be used to estimate the impact of cooling centers on mortality rates.
- Eisenman et al. (2016) found that in Maricopa County, AZ, as temperatures increase, mortality from heat-related illness increases less in census tracts with more publicly accessible cooled spaces. The model was not estimated at an individual level, and the

---

[202] Ebi, K.L., Teisberg, T.J., Kalkstein, L.S., Robinson, L. and Weiher, R.F., 2004. Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–98. Bulletin of the American Meteorological Society, 85(8), pp.1067-1074.

[203] Bouchama, A., et al., 2007. *Prognostic factors in heat wave related deaths: a meta-analysis*. Arch Intern Med. 167(20): p. 2170-6

[204] Vandentorren, S., et al., *August 2003 heat wave in France: risk factors for death of elderly people living at home*. Eur J Public Health, 2006. 16(6): p. 583-91.18.

[205] Palecki, M.A., S.A. Changnon, and K.E. Kunkel, 2001. *The nature and impacts of the July 1999 heat wave in the midwestern United States: learning from the lessons of 1995*. Bull. Amer. Meteor. Soc.,82(7): p.1353-1367

location and study design do not make it transferrable to Delaware, but the study does support the conceptual basis for cooling centers as a protective measure.[206]

- Fechter-Leggett et al. (2016) did not examine mortality but instead assessed heat stress emergency department visits in 14 states with complete data (not including Delaware but including nearby New Jersey and New York, and four other Northeast states) from 2005 to 2010. The study found higher emergency department visit rates in rural compared to urban regions and hypothesizes that this may have had to do with lower access to cooling centers or other interventions in rural areas. The study did find that urban residents had a higher incidence of hospital admission or death following an emergency department visit.[207]

From our analysis of these literature, and other information derived from the 2018 Center for Disease Control literature review (Widerynski et al. 2018), we conclude that mortality rates with and without cooling center access may be best characterized by the Bouchama et al. (2007) meta-analysis. There are relatively wide error bounds on those estimates, however. As such, we conclude that it would be prudent to use the low end of the Bouchama et al. 95 percent confidence interval (a 50 percent reduction in effect for populations with access to cooling centers) to reflect uncertainty in transferring the Bouchama et al. (2007) estimate to Delaware. Important factors which remain unknown or uncertain in transferring this estimate to the Delaware context include: (1) the possible significance of differences in population susceptibility in European and midwestern cities relative to Delaware; (2) the lack of Delaware-specific data on individual use of cooling centers (e.g., survey data in several locations reveals that many individuals would not be comfortable taking refuge in a designated cooling center); (3) options in Delaware to make use of informal cooling centers, as some researchers note that access to an indoor mall may provide sufficient respite to alleviate heat stress during daytime hours; and (4) the general lack of information to measure or estimate current access to cooling centers in Delaware. As a result of these uncertainties, the effect of lack of access to cooling centers in Delaware may be much higher or much lower than our estimates. The data sources used in this analysis are summarized in **Table 7-13**.

TABLE 7-13. LIMITED ACCESS TO COOLING CENTERS ANALYSIS DATA SOURCES

DATA	DESCRIPTION	SOURCE
Per capita mortality	For three cities near Delaware, for each RCP and era	Mills, D., Schwartz, J., Lee, M. Sarofim, M., Jones, R., Lawson, M. Duckworth, M. and Deck, L. 2014. Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. Climatic Change, 131, 83-95.
Population projections	2010-2100, by county	U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.
Effect of cooling center access on heat stress mortality	Up to 50%, among population that has limited access to cooling centers	Bouchama, A., Debhi, M., Mohamed, G., Matthies, F., Shoukri, M. and Menne, B. 2007. Prognostic factors in heat wave related deaths: a meta-analysis. Archives of Internal Medicine. 167(20), 2170-6.

---

[206] Eisenman et al. 2016. Heat Death Associations with the built environment, social vulnerability, and their interactions with rising temperature. Health and Place. 41:89-99.

[207] Fechter-Leggett, E.D., A. Vaidyanathan, and E. Choudhary, 2016. *Heat stress illness emergency department visits in national environmental public health tracking states, 2005-2010.* Journal of Community Health. 41(1): p. 57-69

Results:

The results in **Table 7-14** below provide an initial estimate of the portion of heat-related mortality (estimated in Chapter 4.1 of this report) that may be attributed to lack of access to cooling centers. Therefore, these results should be interpreted as a subset of, not an addition to, the total impacts presented in Chapter 4.1. The estimates reflect an application of the low end of the effect estimate in Bouchama et al. (2007) – that is, that up to half of the urban population of Delaware might successfully avoid the risk of extreme heat mortality if there were 100 percent attendance at cooling centers for the population at risk of heat related mortality. We think it is reasonable to assume that currently, in Delaware, the attendance at cooling centers during high heat events is likely be much less than 100 percent and is probably very low.

The results in **Table 7-14** show that the total economic impacts associated with heat-related health mortality from lack of access to cooling centers are projected to more than triple between near century and late century, under RCP4.5, and increase by an order of magnitude under RCP8.5 — consistent with the trend for overall heat mortality risk from Chapter 4.1. Wilmington is projected to have the largest damages, driven by a larger population than Dover and Seaford.

TABLE 7-14. ANNUAL ECONOMIC IMPACTS OF HEAT-RELATED MORTALITY ATTRIBUTED TO LACK OF ACCESS TO COOLING CENTERS AND CLIMATE CHANGE ($MILLION)

Economic impacts defined measured as VSL for mortality, reported in millions of dollars (2019) per year. Results reflect the average of results for six GCMs, relative to a 1986-2005 baseline. Values may not sum due to rounding.

	NEAR CENTURY (2020-2039)		MID-CENTURY (2040-2059)		LATE-CENTURY (2080-2099)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Kent County (Dover)	$1.5	$1.2	$3.1	$2.5	$25	$5
New Castle County (Wilmington)	$2.2	$1.8	$4.1	$3.3	$28	$6
Sussex County (Seaford)	$0.20	$0.16	$0.35	$0.27	$2.4	$0.5
Delaware Total	**$3.9**	**$3.1**	**$8**	**$6**	**$55**	**$12**

Limitations:

- To our knowledge, there is no current epidemiological literature that directly estimates heat mortality effects in Delaware's urban areas, or in other Delaware locations. As a result, we use a health impact function transfer approach based on impacts estimated in other cities in the Mid-Atlantic region. The uncertainties introduced by this transfer are unknown.
- The effect estimate we used is at the low end of the 95 percent confidence interval from the selected study (Bouchama et al. 2007), in an attempt to avoid overestimating the effect attributable to lack of access to cooling centers. Results from the studies surveyed in that meta-analysis reflect historic conditions, which can evolve over time, including the historically lower availability of public options for air-conditioned spaces and the historically low awareness within the at-risk population of the potentially deadly effects of extreme heat. If current awareness of the hazard is relatively high in Delaware — and

if many residents have access to cooling centers and are willing to use them — then our assumption may suggest that the effect estimate for current and future conditions could be even lower than the low end of the confidence interval.

- We assume that baseline conditions concerning the availability of and access to cooling centers in Delaware is similar to that in the cities studied in Bouchama et al. (2007), but we have no empirical means to measure those parameters either in the study's cities or in urban areas in Delaware. One recent study (Nayak et al. 2016) found that only 29 percent of counties in New York State implemented cooling center access, suggesting they may remain infrequently used in many locations.[208]
- As noted above, some evidence exists to suggest that rural areas may also experience significant heat mortality effects, and may also have more limited access to some cooling center options (e.g., shopping malls). Omission of rural areas in our analysis may therefore result in underestimation of the impact of both heat stress on overall mortality and on the attribution of this excess mortality to rural area residents.
- We assume that baseline conditions of individual behavior, particularly the likelihood of individuals being willing to utilize cooling centers, remain constant through our projection period. Survey evidence suggests that even with more availability of cooling centers, many individuals are reluctant to move to a cooling center (see Widerynski et al. 2018, and especially Kousatsky et al. 2009; Alberini et al. 2011; Cusack et al. 2013; Sampson et al. 2013; and Lane et al. 2013).[209] This unwillingness of individuals to use cooling centers supports the use of estimates in Bouchama et al. (2007), which also suggests low use of cooling centers among populations in the studies they assessed.

---

[208] Nayak, S.G., et al., 2016. *Surveying local health departments and county emergency management offices on cooling centers as a heat adaptation resource in New York State*. Journal of Community Health, 2016:p.1-8.

[209] Kosatsky, T., et al., *Heat awareness and response among Montreal residents with chronic cardiac and pulmonary disease*. Canadian Journal of Public Health/Revue Canadienne de Sante'e Publique, 2009:p.237-240.

Alberini, A., W. Gans, and M. Alhassan, *Individual and public-program adaptation: coping with heat waves in fve cities in Canada*. International Journal of Environmental Research and Public Health,2011. 8(12): p. 4679-4701.

Cusack, L., et al., *Extreme weather-related health needs of people who are homeless*. Australian Journal of Primary Health, 2013. 19(3): p. 250-255.

Sampson, N.R., et al., *Staying cool in a changing climate: Reaching vulnerable populations during heat events*. Global Environmental Change, 2013. 23(2): p. 475-484

Lane, K., et al., *Extreme Heat Awareness and Protective Behaviors in New York City*. Journal of Urban Health, 2014. 91(3): p. 403-414.

APPENDIX A | GLOSSARY

Accretion rate: As applied to salt marsh areas, accretion is defined as growth by deposition of suspended particles during flooding and by accumulation of plant material (both roots and decomposed material from plants growing in the marsh). The rate is usually expressed as centimeters or inches per year.

Climate stressor: A climatic condition or event, such as temperature, precipitation, sea level rise, or storm surge, that exacerbates potential hazards.

Consumer surplus: The welfare gained by consumers by consuming a good or service, calculated as the difference between the price paid and the willingness-to-pay for the good or service at a given quantity.

Contaminated sites: In this study, contaminated sites include all sites regulated under the Delaware Hazardous Substance Cleanup Act.

Delay costs: The public welfare loss (i.e. the lost perceived value to society) associated with transportation delays, including passenger and freight delays.

Direct expenses: Direct costs, or “out-of-pocket” expenses. For example, repair costs and costs of hospitalization.

Economic impacts: Effects of climate change measured in economic terms, including welfare changes, direct expenses, and lost revenues.

Ecosystem services: Any positive benefit that wildlife or ecosystems provide to people.

Emergency responses: Public safety response to an emergency situation, including fire response, emergency medical service, and hospitalizations.

Fatal risk: A circumstance or hazardous activity that has the potential to result in a fatality or death. In environmental contexts, fatal risk is usually presented when a population is exposed to a potentially fatal hazard, such as a storm surge or air pollution.

Fragility curve: A mathematical representation of the probability of structural damage in response to a physical stress. An example would be the probability of a bridge failure expressed as a function of the stress of flowing water on the bridge piers. In this example, a system of fragility curves might be developed (e.g., one curve for each class of bridge condition or age) to further represent the role of bridge condition as a factor affecting bridge vulnerability to damage.

High tide flooding: Scenarios in which tidal waters, in the absence of storm surge or rainfall, temporarily rise above a level that results in standing water on low-lying roads or seawater entering stormwater systems. Also known as nuisance flooding or sunny-day flooding.

Impact categories: Each of the 26 individual analyses in this report, representing categories of potential economic impact from climate change that may be of interest to state agencies.

Mean higher high water: Average height of the highest tide recorded at a tide station each day during a historical recording period. Mean higher high water is a commonly used vertical datum (i.e., surface of zero elevation used as a point of reference) to provide a baseline for measuring sea level rise or storm surge.

Morbidity: When used in medical or fatal risk terms, the number of people who have a disease or a symptom of disease (often but not always non-fatal) or the amount of disease within a population.

Mortality: When used in medical or fatal risk terms, the number of deaths in a certain population. Often expressed as mortality rate (i.e., the number of deaths in a certain population over a certain period of time).

Proactive adaptation: Adaptation decisions for infrastructure impact categories that include action and investment in risk mitigation, based on some level of foresight of future conditions.

Reactive adaptation: Adaptation decisions for infrastructure impact categories to repair damage, but without forward planning to avoid future damage.

Saltwater intrusion: Infiltration of saline water into freshwater aquifers, resulting in degradation of useable freshwater.

Storm surge: Coastal flooding associated with low-pressure weather systems during storm events.

Welfare: A measure of wellbeing or quality of life used in economics to evaluate changes in conditions.

APPENDIX B | CLIMATE DATA COMPARISON ANALYSIS

In conducting this economic analysis of climate change impacts in Delaware, IEc relied on the findings of a broad array of prior U.S. EPA studies that used climate projections from the Localized Constructed Analogues (LOCA) dataset (Pierce et al, 2014). This appendix compares the LOCA projections to the Delaware-specific projections developed for the 2014 Delaware Climate Change Impact Assessment (referred to as the DNREC dataset in this appendix). These two datasets were developed with different aims and are thus configured differently.

B.1 DNREC DATA

The DNREC data were developed by ATMOS Research & Consulting (Hayhoe et al., 2013) for application in the 2014 DNREC Delaware Climate Change Impact Assessment. The ATMOS report states that the "methods represent updated versions of those used in the 2007 Northeast Climate Impact Assessment (Frumhoff et al., 2007) and the Second U.S. National Climate Assessment, Global Climate Change Impacts in the United States (USGCRP, 2009), and are consistent with those used in the Climate Science section of the upcoming Third U.S. National Climate Assessment (Walsh et al., 2014)."

The DNREC projections contain nine General Circulation Models (GCMs) with two representative concentration pathways (RCPs) each, producing eighteen unique simulations. Specifically, these nine GCMs contain five simulations from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) and three simulations from CMIP3. The methodology statistically downscales each of these simulations to each of the 14 weather stations in Delaware using the Asynchronous Regional Regression Model. Details of this process are available in Hayhoe et al. (2013).

B.2 LOCA DATA

The LOCA data downscale climate model projections for the purpose of, among other things, better representing extreme weather events and adding finer-scale detail to global climate models. These data were used in the U.S. EPA's 2017 Climate Change Impacts and Risk Analysis (CIRA) project, developed to inform the Fourth National Climate Assessment of the U.S. Global Change Research Program (USGCRP, 2018).

This work uses historical data from Livneh et al. (2015) and the LOCA downscaling technique to downscale 32 CMIP5 GCMs, each with two RCPs. The results are daily gridded 1/16th degree data covering the 1950-2005 historical period and the 2006-2100 (or 2099 for some GCMs) future period for North America, from central Mexico to Southern Canada. IEc has processed changes in climate projections for 12 of the 32 GCMs; these 12 are the basis of the comparison below. Note that the economic impact analyses conducted for CIRA (and in the main body of this report) used only six of the 12 GCMs that were processed.

B.3 COMPARISON OF DNREC TO LOCA DATA

In total, the DNREC dataset includes bias corrected and downscaled data for 18 GCM-RCP combinations. The LOCA dataset used here includes 24 GCM-RCP combinations, eight of which overlap with the DNREC set. **Tables B-1** through **B-3** summarize changes in climatic variables across these full sets of GCM-RCP combinations for Kent County.[210] To develop the values in these tables, data from weather stations (for DNREC) and 1/16th degree grid cells (for LOCA) within Kent County are averaged.

Tables B-1 and **B-2** display the changes in precipitation and temperature from the respective historical baselines for the DNREC and LOCA datasets, respectively.

---

[210] The DNREC data was available at the County level. We selected Kent County as the central county as the example case for comparison.

TABLE B-1. DNREC CHANGES IN CLIMATIC VARIABLES FOR KENT COUNTY

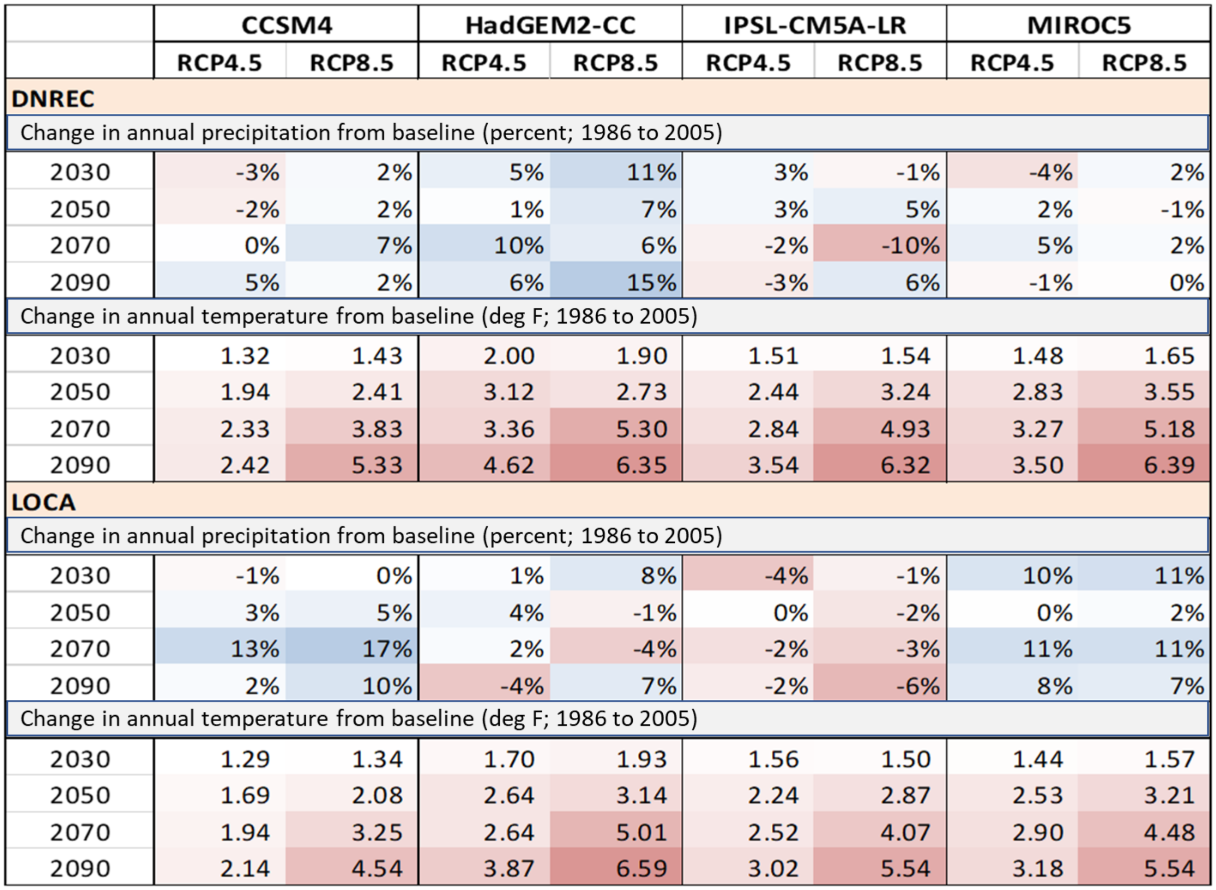
GCM	CCSM4		CNRM-CM5		CSIRO-MK3.6.0		HadGEM2-CC		inmcm4		IPSL-CM5A-LR		MIROC5		MPI-ESM-LR		MRI-ESM-LR	
RCP	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Change in annual precipitation from baseline (percent; 1986 to 2005)																		
2030	-3%	2%	14%	4%	-7%	-2%	5%	11%	6%	-1%	3%	-1%	-4%	2%	17%	11%	-1%	-2%
2050	-2%	2%	5%	8%	5%	-10%	1%	7%	0%	-4%	3%	5%	2%	-1%	6%	20%	0%	13%
2070	0%	7%	6%	12%	1%	15%	10%	6%	7%	8%	-2%	-10%	5%	2%	14%	6%	8%	10%
2090	5%	2%	12%	18%	5%	-3%	6%	15%	7%	-5%	-3%	6%	-1%	0%	9%	14%	9%	16%
Change in annual temperature from baseline (deg F; 1986 to 2005)																		
2030	1.32	1.43	0.86	1.15	1.16	1.26	2.00	1.90	0.71	0.84	1.51	1.54	1.48	1.65	0.69	1.35	0.73	0.71
2050	1.94	2.41	1.58	2.51	2.24	2.02	3.12	2.73	0.94	1.39	2.44	3.24	2.83	3.55	1.17	2.41	1.37	1.98
2070	2.33	3.83	2.21	3.40	2.72	4.19	3.36	5.30	1.31	2.44	2.84	4.93	3.27	5.18	1.50	3.49	1.55	2.48
2090	2.42	5.33	2.69	4.65	3.25	5.14	4.62	6.35	1.66	3.34	3.54	6.32	3.50	6.39	1.98	5.00	1.77	3.72

TABLE B-2. LOCA CHANGES IN CLIMATIC VARIABLES FOR KENT COUNTY

GCM	ACCESS1-3		CanESM2		CCSM4		GFDL-CM3		GISS-E2-R		HadGEM2-CC		HadGEM2-ES		IPSL-CM5A-LR		IPSL-CM5A-MR		MIROC5		MIROC-ESM-CHEM		MRI-CGCM3	
RCP	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Change in annual precipitation from baseline (percent; 1986 to 2005)																								
2030	1%	-1%	-3%	-5%	-1%	0%	10%	5%	-6%	2%	1%	8%	-1%	6%	-4%	-1%	3%	-2%	10%	11%	-3%	2%	-5%	-1%
2050	3%	-3%	0%	0%	3%	5%	12%	12%	0%	4%	4%	-1%	2%	0%	0%	-2%	-5%	5%	0%	2%	2%	5%	-2%	-2%
2070	3%	10%	1%	-3%	13%	17%	19%	15%	8%	0%	2%	-4%	1%	-4%	-2%	-3%	3%	0%	11%	11%	-1%	4%	0%	9%
2090	6%	11%	7%	3%	2%	10%	17%	17%	6%	5%	-4%	7%	0%	5%	-2%	-6%	9%	3%	8%	7%	6%	3%	4%	6%
Change in annual temperature from baseline (deg F; 1986 to 2005)																								
2030	1.03	1.30	1.90	2.03	1.29	1.34	1.90	1.99	1.27	1.33	1.70	1.93	1.73	1.74	1.56	1.50	1.52	1.44	1.44	1.57	2.03	2.30	0.47	0.48
2050	1.90	2.44	2.62	3.10	1.69	2.08	2.72	3.25	1.48	2.20	2.64	3.14	3.00	3.28	2.24	2.87	1.98	2.56	2.53	3.21	2.78	3.54	1.10	1.69
2070	2.51	3.95	3.10	4.61	1.94	3.25	3.67	5.01	1.81	2.78	2.64	5.01	3.71	5.02	2.52	4.07	2.39	4.05	2.90	4.48	3.66	4.72	1.32	2.18
2090	2.79	4.57	3.22	5.86	2.14	4.54	3.68	6.36	1.95	3.68	3.87	6.59	4.05	6.50	3.02	5.54	2.63	5.22	3.18	5.54	3.50	6.76	1.47	3.41

Table B-3 compares only the overlapping eight GCM-RCP combinations, allowing us to compare potential differences in bias correction and downscaling methodologies between the datasets. In terms of temperature, the table shows similar temporal trends and patterns of intensity between models and RCPs. Overall, absolute changes in temperature are close in earlier eras and diverge somewhat by 2090, although the differences are small enough that they should produce similar results in the high-level analyses used in our work. Precipitation, which commonly has a less clear and linear signal over time and space in climate projections, shows a greater degree of difference between DNREC and LOCA. These differences could also reflect the fact that the DNREC dataset is developed by averaging climate changes at several specific points in each county, whereas LOCA averages grid cells across the entire area.

TABLE B-3. CHANGES IN CLIMATIC VARIABLES FOR THE OVERLAPPING LOCA AND DNREC GCMS



	CCSM4		HadGEM2-CC		IPSL-CM5A-LR		MIROC5	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
DNREC								
Change in annual precipitation from baseline (percent; 1986 to 2005)								
2030	-3%	2%	5%	11%	3%	-1%	-4%	2%
2050	-2%	2%	1%	7%	3%	5%	2%	-1%
2070	0%	7%	10%	6%	-2%	-10%	5%	2%
2090	5%	2%	6%	15%	-3%	6%	-1%	0%
Change in annual temperature from baseline (deg F; 1986 to 2005)								
2030	1.32	1.43	2.00	1.90	1.51	1.54	1.48	1.65
2050	1.94	2.41	3.12	2.73	2.44	3.24	2.83	3.55
2070	2.33	3.83	3.36	5.30	2.84	4.93	3.27	5.18
2090	2.42	5.33	4.62	6.35	3.54	6.32	3.50	6.39
LOCA								
Change in annual precipitation from baseline (percent; 1986 to 2005)								
2030	-1%	0%	1%	8%	-4%	-1%	10%	11%
2050	3%	5%	4%	-1%	0%	-2%	0%	2%
2070	13%	17%	2%	-4%	-2%	-3%	11%	11%
2090	2%	10%	-4%	7%	-2%	-6%	8%	7%
Change in annual temperature from baseline (deg F; 1986 to 2005)								
2030	1.29	1.34	1.70	1.93	1.56	1.50	1.44	1.57
2050	1.69	2.08	2.64	3.14	2.24	2.87	2.53	3.21
2070	1.94	3.25	2.64	5.01	2.52	4.07	2.90	4.48
2090	2.14	4.54	3.87	6.59	3.02	5.54	3.18	5.54

Table B-4 aggregates the data for all three counties to compare the minimum and maximum changes in precipitation and temperature across all GCM-RCP combinations for DNREC and LOCA, across all four eras (2030, 2050, 2070, and 2090), relative to the baseline (1986-2005). The upper table shows results for the eight GCM-RCP combinations that overlap between the DNREC and LOCA datasets, and the lower table shows results for all LOCA and DNREC models. The comparison of overlapping GCMs allows us to understand how the methodologies used to develop the two climate datasets compare. The comparison of the full datasets provides insights into the differences in climate stressors evaluated in each study. Overall, among the overlapping GCM-RCP combinations, DNREC shows slightly larger maximum projected reductions in precipitation, whereas LOCA shows larger maximum projected increases in precipitation. Differences in the minimum and maximum changes in projected temperature are very similar. As mentioned earlier, there are several possible sources for discrepancies in these ranges, including differences in downscaling methodology and the difference in spatial representation of the final products (points versus a mesh grid surface). Similar results are seen in the comparison of the two full climate datasets.

TABLE B-4. MINIMUM AND MAXIMUM CLIMATIC VARIABLE CHANGES FOR DNREC AND LOCA DATASETS

CLIMATIC CHANGES FOR OVERLAPPING DATASETS
4 GCMS X 2 RCPS

County	Dataset	Temperature Change (˚F)		Precipitation Change	
		Minimum	Maximum	Minimum	Maximum
Kent	DNREC	1.32	6.39	-10%	15%
	LOCA	1.29	6.59	-6%	17%
New Castle	DNREC	1.27	6.60	-7%	16%
	LOCA	1.30	7.00	-2%	17%
Sussex	DNREC	1.44	6.86	-9%	11%
	LOCA	1.08	5.82	-7%	16%

CLIMATIC CHANGES FOR FULL DATASETS
12 LOCA GCMS AND 9 DNREC GCMS (BOTH COVERING 2 RCPS)

County	Dataset	Temperature Change (˚F)		Precipitation Change	
		Minimum	Maximum	Minimum	Maximum
Kent	DNREC	0.69	6.39	-10%	20%
	LOCA	0.47	6.76	-6%	19%
New Castle	DNREC	0.66	6.60	-7%	17%
	LOCA	0.36	7.00	-9%	26%
Sussex	DNREC	0.71	6.86	-9%	14%
	LOCA	0.38	6.42	-7%	19%

REFERENCES (APPENDIX B)

Division of Energy and Climate: Delaware Department of Natural Resources and Environmental Control. 2014. Delaware Climate Change Impact Assessment. Available at http://www.dnrec.delaware.gov/energy/Documents/Climate%20Change%202013-2014/DCCIA%20interior_full_dated.pdf

EPA. 2017. Avoiding and Reducing Long-term Risks of Climate Change: A Technical Report for the Fourth National Climate Assessment. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-17-001. Available at https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=OAP&dirEntryId=335095

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

Hayhoe, K., A. Stoner, and R. Gelca. "Climate change projections and indicators for Delaware." *Journal of ATMOS Research & Consulting* 1 (2013): 1-56.

Livneh, B., T. J. Bohn, D. W. Pierce, F. Munoz-Arriola, B. Nijssen, R. Vose, D. R. Cayan, and L. Brekke, 2015: A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950-2013. Scientific Data, v. 2, article 150042 (2015). doi:10.1038/sdata.2015.42.

Pierce, David W., Daniel R. Cayan, and Bridget L. Thrasher. "Statistical downscaling using localized constructed analogs (LOCA)." *Journal of Hydrometeorology* 15.6 (2014): 2558-2585.

Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014) Chapter 2: Our Changing Climate. In: The Third U.S. National Climate Assessment. In press.

U.S. Global Change Research Program (USGCRP). (2009). Global climate change impacts in the United States. Cambridge University Press. http://www.globalchange.gov/usimpacts/

USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.