IEc

ECONOMIC VALUATION OF WETLAND ECOSYSTEM SERVICES IN DELAWARE

Final Report | June 2011

prepared for:

Delaware Department of Natural Resources and Environmental Control

Division of Water Resources

89 Kings Highway

Dover, DE 19901

prepared by:

Industrial Economics, Incorporated

2067 Massachusetts Avenue

Cambridge, MA 02140

INDUSTRIAL ECONOMICS, INCORPORATED

TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

CVPESS	Committee on Valuing the Protection of Ecological Systems and Services
DEM	Digital Elevation Model
DEMON	Delaware Environmental Monitoring and Observing Network
DEOS	Delaware Environmental Observing System
DEWAP	Delaware Wildlife Action Plan
DNREC	Delaware Department of Natural Resources and Environmental Control
FEMA	Federal Emergency Management Agency
GIS	Geographic Information Systems
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
LULC	Land Use/Land Cover
Mg	Megagrams
MHHW	Mean Higher High Water
mm	Millimeters
NFIP	National Flood Insurance Program
NJDEP	New Jersey Department of Environmental Protection
NRCS	Natural Resources Conservation Service
NWI	National Wetlands Inventory
SAB	Science Advisory Board
SCS	Soil Conservation Service
SGCN	Species of Greatest Conservation Need
SSURGO	Soil Survey Geographic Database
USDA	United Stated Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation

ACKNOWLEDGEMENTS

This project was managed under the direction of Amy Jacobs, Watershed Assessment Section of the Delaware Division of Natural Resources and Environmental Control (DNREC). Multiple staff at DNREC also provided valuable review and comment on the analysis, including Karen Bennett (Division of Fish and Wildlife), Mark Biddle (Watershed Assessment Section), Lyle Jones (Division of Water Resources), Michael Powell (Division of Soil and Water Conservation), as well as Austin Short at the Delaware Department of Agriculture.

A number of experts at The Natural Capital Project also provided guidance in the application of the InVEST models, including Dr. Stephen Polasky (University of Minnesota), Dr. Driss Ennaanay (Stanford University), Dr. Kent Kovacs (University of Minnesota), and Dr. Derric Pennington (University of Minnesota). In addition, Kevin McGuckin (Conservation Management Institute, Virginia Tech) assisted with interpretation of the Delaware wetland map data.

SUMMARY

Wetland ecosystems throughout the State of Delaware are threatened by expanding development associated with a growing population. Decreased quality and quantity of wetlands results in a reduction in their ability to provide valuable ecosystem services such as climate regulation, water purification, flood control, and recreational opportunities. The objective of this analysis is to value changes in ecosystem services that may result from continued trends in wetland decline in Delaware. Specifically, our analysis values the change in the delivery of the ecosystem services associated with a 1.2 percent decline in wetlands across the state (3,132 acres of wetland loss) over a 15 year time frame (2007 to 2022).

STRENGTHS OF THE ANALYTIC FRAMEWORK

In recent years, decision-makers have placed increasing focus on valuing ecosystem services in order to capture as complete an accounting as possible of the costs and benefits of land and resource management programs and policies, such as wetland conservation and restoration. The demand for this information has generated significant debate among the ecological and economics communities regarding the proper framework for valuing ecosystem services.

Our analysis applies an existing, spatially-explicit modeling tool, the Integration Valuation of Ecosystem Services and Tradeoffs (InVEST), to quantify tradeoffs in the delivery, geographic distribution, and economic values of ecosystem services due to projected wetland decline in Delaware.[1] InVEST incorporates linked ecological production functions and economic valuation models to identify biophysical relationships between wetland resources and associated ecosystem services. The strengths of this approach, as described in more detail in Section 1 of this report, include:

1. The spatially-explicit models are able to account for interactions with the surrounding landscape in determining the value of services provided. In other words, the value of a given wetland in buffering against flooding is dependent on the situation of that wetland within the broader landscape (e.g., elevation, surrounding vegetation types and density), as well as the proximity of infrastructure vulnerable to damage from flooding.
2. Our analysis values the net change in services associated with projected wetland decline. For example, where wetlands are converted to agriculture, the model quantifies the <u>difference</u> in services, such as carbon storage, provided by the landscape rather than assuming a total loss in carbon storage due to the lost wetland. Quantifying the net change as opposed to an absolute value of services provides more meaningful estimates to inform policy.
3. We provide decision-makers with information on both biophysical and economic endpoints. In some cases, a biophysical change may provide more information to land managers than economic values of services. In addition, not all services are equally amenable to

[1] The InVEST tool was developed by ecologists and economists at The Natural Capital Project. For more information on The Natural Capital Project and InVEST, see http://www.naturalcapitalproject.org/home04.html.

monetization. InVEST only emphasizes monetization for individual service categories insofar as there exist data and methods consistent with established economic principles that are transferable to the site of interest.

SUMMARY OF RESULTS

We estimate the biophysical change and the associated economic values of a 1.2 percent decline in wetlands in Delaware, as follows.

Carbon storage:

- Loss of 194,417 metric tons of carbon storage.
- Social cost of additional carbon in the atmosphere (i.e., damages associate with climate change) is $19.9 million (present value over 15 years). This is equivalent to an annualized cost of $1.59 million.

Water purification:

- Increase in nitrogen delivered to waterways of 1.2 percent.
- Increase in phosphorus delivered to waterways of 0.9 percent.
- Increase in sediment delivered to waterways of 1.3 percent.
- Increased municipal water treatment costs of $9.67 million (present value over 15 years). This is equivalent to an annualized cost of $770,000.

Inland flood control:

- Increases in flood heights and flood area following a storm event in floodplains of rivers at four case study sites across the state (specific changes variable by location reported in Section 4 and Appendix A).
- Damages to residential structures in the Red Clay Creek watershed of $720 to $21,200 (present value over 15 years). This is equivalent to an annualized cost of $57 to $1,690 at this site.

Coastal storm protection:

- Increases in flood heights and flood area following coastal storm surge event across the state (specific changes variable by location reported in Section 4 and Appendix A).
- Damages to residential structures of $47,600 to $301,000 (present value over 15 years). This is equivalent to an annualized cost of $3,790 to $23,900.

Wildlife protection:

- Direct habitat loss and increased habitat degradation. Specific changes vary by habitat type across the state, as described in Section 5 and Appendix B.
- We do not include an economic endpoint for this service due to the difficulty in establishing quantitative relationships between the projected wetland decline and species populations. We do, however, provide contextual information in Section 5 on the

economic value of ecosystem services associated with healthy wetland habitats in Delaware, such as fishing, hunting, and wildlife viewing.

INTERPRETING THE RESULTS

We estimate an annualized loss of approximately $2.4 million in the value of the ecosystem services analyzed. Considering recent trends, these losses derive from realistic assumptions regarding potential future wetland decline within the state. Importantly, this should not be interpreted as a total value of 3,132 wetland acres in Delaware, nor should an average per acre value of wetlands be inferred from this estimate. The value may be considered a lower bound estimate of the ecosystem service losses associated with the projected wetland losses. That is, the impacts reflect decreases in the value of ecosystem services due to our 1.2 percent wetland loss scenario (i.e., our analysis assumes 98.8 of wetlands in the state remain and continue to provide ecosystem services). Should the rate of wetland loss increase, or extend beyond the 15 year timeframe of the analysis, these ecosystem service losses would increase.

In addition, these values reflect only those service categories described above. We do not account for other categories of ecosystem service associated with the wetlands for which data or model limitations prevented reliable valuation, for example, recreation, commercial fishing, and aesthetic or cultural values. The extent to which our specific wetland loss scenario reduces the values of these services is uncertain. The projected conversion of the lost wetlands to agricultural and residential development, however, would lead to a net reduction in the capacity of the Delaware landscape to support recreation activities such as hunting, fishing, and wildlife viewing.

The values for each service category are also net of the values for these services provided by the substitute land use. For example, where wetlands are replaced by agricultural land use, there is a reduction in the carbon storage capacity of the land, but not a total loss. Thus, the results do not reflect the total value of the lost wetland in storing carbon.

A significant factor contributing to our understating ecosystem service losses is the case study approach applied to quantify increased flood damages for the inland flood control analysis. The estimated damage to residential structures represents a relatively low ecosystem service value loss compared to the other services evaluated (e.g., carbon storage and water purification). This result does not indicate that buffering against flooding is a less valuable ecosystem service of the wetlands for the following reasons:

- The residential damage estimate is not a statewide value, as are the other service values provided. The damages reflect only those increased damages to residential structures at one location (along Red Clay Creek). We do not use these estimates as a scalar to calculate damages at the regional or State level because incremental flooding due to wetland loss varies significantly by site.
- The damages reflect the expected value over the 15 year time frame of just one type of storm event with a four percent chance of occurrence in each year (a 25 year rainfall event). These damages would be additive to the damages associated with other rainfall events. Less intense storms may generate less damage, but would occur with greater frequency. On the other hand, more extreme rainfall events would likely be associated with greater damages but would have a lower probability of occurrence in a given year.

- Estimated damages only reflect one type of flooding: stormwater pooling around streams and watershed outlet points. The analysis does not account for additional flooding potential associated with, for example ponding of stormwater in inland areas, such as agricultural fields.
- The flood damages pertain only to flooding of residential structures. Other types of productive land use (commercial and industrial developments, etc.) may likewise experience damages in this and in other areas of the state.

We therefore present the case study results to provide insight into the role that wetlands play in mitigating flooding. The results are not, however, reflective of the total losses in the capacity of the Delaware landscape to buffer flooding due to the projected wetland losses.

Overall, the annualized estimate of $2.4 million is a lower bound estimate of ecosystem service losses due to projected wetland losses in Delaware over 15 years. This result does, however, indicate that losses of wetland ecosystem services within the timeframe of this analysis would likely be in the millions of dollars annually across the state. If wetland loss trends continue, this value would most likely increase over time as wetland ecosystems grow increasingly scarce.

IMPLICATIONS FOR LAND AND RESOURCE MANAGEMENT IN DELAWARE

The results of this analysis provide a deeper understanding of the types and potential magnitude of economic benefits expected to result from efficient and effective conservation and management of the state's wetland resources. The analysis demonstrates that wetlands, relative to the residential, commercial, and agricultural development land uses threatening them, effectively purify water resources, buffer flooding due to storm events, provide habitat for sensitive and recreationally-valuable species, and contribute to climate regulation by storing carbon.

This analysis may be used to identify where wetland conservation efforts should be focused to maximize ecosystem service values. Because the results of the analysis are spatially explicit, we can compare the ecosystem service losses associated with the loss of wetlands in different locations across the state. For example, wetlands that are surrounded by agricultural land may be particularly valuable in filtering nutrients from the agricultural lands compared to wetlands surrounded by forest.

In addition, this analysis may be referenced to support adaptation initiatives, such as floodplain management. The inland flood analysis demonstrates that wetlands are effective in reducing flood heights and, in some cases, the extent of areas vulnerable to flooding. Flood damages avoided due to the presence of wetlands significantly vary by site. The value of avoided damages is a function of multiple site-specific factors, in particular the capacity of the wetland to store stormwater runoff, and the number of structures within the flooded area.

RECOMMENDATIONS AND NEXT STEPS

As described above, data and model limitations prevented a complete, statewide valuation of some categories of ecosystem services. Much of the uncertainty in our results is related to the flood analyses. Our coastal storm surge analysis applies a simplified approach (see Section 4) to identifying flood area and flood heights due to storm-related surge along the Delaware coast. Since the development of this analysis, a version of InVEST (Marine InVEST) has been released that models coastal storm surge. This model may be applied in the future to provide additional information regarding this service in Delaware. An additional recommendation to improve the precision of the storm surge analysis is to measure surge attenuation due to the presence of coastal wetlands in Delaware. Absent site-specific information on the effectiveness of Delaware coastal wetlands in attenuating surge, our analysis applies a surge attenuation rate from wetland studies in Louisiana.

Information regarding wetland depths across the state would improve analyses of the value of wetlands in buffering against flooding. A key factor in in the inland flood control analysis is the capacity of wetlands to store stormwater as it travels across the landscape. Absent spatially-explicit information on wetland depths, we evaluate this service according to two wetland depth assumptions (zero and one meter).

In addition, mapping commercial, industrial, and residential structures across the state would provide better information to estimate damages due to both inland flooding and coastal storm surge. While these data are available in some areas of the state, geospatial data describing locations of infrastructure across the state are incomplete. This information would be helpful in identifying where increases in flood heights or flooded areas are likely to damage infrastructure. Collecting information on flood damages related to flood heights within Delaware would also benefit future flood damage analyses. Absent historic information on damages associated with particular flood heights in homes in Delaware, our analysis applies national average estimates of flood damages on residential properties. Improved data would refine the damage function applied to estimate flood damages.

Finally, through the course of developing this analysis, we have aggregated significant amounts of data linking land use in Delaware to the provision of ecosystem services. This information may be refined and augmented over time as new information becomes available, and applied to model the changes in ecosystem services associated with other land use changes or land management policies in Delaware. For example, the InVEST model data developed for Delaware may be used to value the effects on ecosystem services of the conversion of forests to development, or the restoration of specific wetland areas.

SECTION 1 | INTRODUCTION AND FRAMEWORK

Wetlands cover over 30 percent of the State of Delaware. Historically, this number was much larger. Wetland ecosystems throughout the state continue to be threatened by expanding development associated with the growing population. Decreased quality and quantity of wetlands result in a reduction in their functional capacity; that is, their ability to provide ecosystem services such as water purification, flood control, carbon sequestration, habitat, and recreational opportunity, is compromised. The focus of this analysis is to evaluate a suite of ecosystem services provided by Delaware's wetlands in order to provide a deeper understanding of the economic benefits expected to result from efficient and effective conservation and management of the state's wetland resources.

Section 1 of this report provides background information on wetland ecosystem services and approaches to valuing these services. We then describe the framework for the analysis and the models applied. This section also summarizes the results of the analysis, along with key assumptions and uncertainties. Sections 2 through 5 of this report detail the data, analytic methods, and results for each of the following wetland ecosystem services:

- Carbon storage;
- Water purification (in terms of reductions in nitrogen, phosphorus, and sediment concentrations);
- Flood protection (both inland flooding and storm surge associated with storm events); and
- Wildlife protection (biodiversity and habitat provisioning).

1.1 BACKGROUND

Wetlands in Delaware can be grouped into the following classifications: estuarine vegetated, estuarine non-vegetated, palustrine aquatic bed, palustrine emergent, palustrine forested, and palustrine scrub-shrub. The Delaware Department of Natural Resources and Environmental Control (DNREC) recently developed enhanced National Wetland Inventory (NWI) maps for the state. These maps characterize the above categories of wetlands according to hydrogeomorphic factors, such as landscape position, landform, water flow path, and waterbody type.

The enhanced NWI maps inform the current distribution of wetlands across the state. This represents the "baseline scenario" for our analysis. The baseline scenario maps allow us to evaluate where and at what level the various services provided by wetlands are currently generated across the state. Applying data from DNREC on historic trends in wetland losses, we then forecast potential losses in wetlands to develop a hypothetical landscape 15 years into the future. This map reflects our "future scenario." The future scenario assumes that no change in wetland conservation and management practices occurs and that, as a result, trends in wetland losses continue. The difference in the values of Delaware wetland services provided between the baseline (2007) and future (2022) scenarios reflect foregone benefits associated with continued wetland decline across the state.

1.1.1 WETLAND ECOSYSTEM SERVICES

Wetlands provide an array of goods and services of value to humans. We refer to these goods and services collectively as "ecosystem services." Ecosystem services are often conflated with ecosystem functions although these concepts are distinct. The Science Advisory Board of the U.S. Environmental Protection Agency (USEPA, 2009) defines ecosystem functions as, "…the characteristic physical, chemical, and biological activities that influence the flows, storage, and transformation of materials and energy within and through ecosystems." On the other hand, ecosystem services are defined as, "…the direct or indirect contributions that ecosystems make to the well-being of human populations."[1] The distinction is grounded in the explicit connection between services and their value to humans.

Tiner (2003 and 2008) describes the following categories of wetland ecosystem functions. The level at which particular wetlands perform the above functions depends on the type, condition, and situation of the wetland within the broader landscape.

- Surface water detention;
- Streamflow maintenance;
- Nutrient transformation;
- Sediment and other particulate retention;
- Coastal storm surge detention;
- Shoreline stabilization;
- Provision of fish and other shellfish habitat;
- Provision of waterfowl and other waterbird habitat;
- Provision of other wildlife habitat;
- Conservation of biodiversity; and
- Carbon sequestration.[2]

For the purposes of valuation, we correlate these functions with wetland ecosystem services, which can be measured in terms that are more meaningful to people. For example, when presented in terms of changes in nutrient loading, it may be difficult for individuals to understand, let alone quantify, how nutrient retention affects their well-being. Water purification services defined in terms of drinking water quality, however, may be more readily understood, and valued in terms of treatment costs. Exhibit 1 describes how the wetland functions described above relate to ecosystem services.

---

[1] U.S. Environmental Protection Agency Science Advisory Board, Committee on Valuing the Protection of Ecological Systems and Services. Valuing the Protection of Ecological Systems and Services: A Report of the EPA Science Advisory Board. May 2009. EPA-SAB-09-012.

[2] Tiner, R.W. Correlating Enhanced National Wetlands Inventory Data with Wetland Functions for Watershed Assessments: A Rationale for Northeastern U.S. Wetlands. U.S. Fish and Wildlife Service, National Wetlands Inventory Program, Region 5, Hadley, MA 2003; Tiner, R.W. "Background on LLWW and Preliminary Wetland Functional Assessment." Memorandum for the Association for State Wetland Managers (ASWM). December 2008.

EXHIBIT 1. WETLAND ECOSYSTEM SERVICES

WETLAND FUNCTION	ASSOCIATED ECOSYSTEM SERVICES
Surface water detention	Flood control
Streamflow maintenance	Water quality Water supply Recreation (e.g., boating, swimming)
Nutrient transformation	Water quality
Sediment and other particulate retention	Water quality
Coastal storm surge detention	Storm protection
Shoreline stabilization	Storm protection
Provision of fish/shellfish habitat	Commercial fishing and shellfishing Recreational fishing and shellfishing
Provision of waterfowl/waterbird habitat	Hunting Wildlife viewing
Provision of other wildlife habitat	Hunting Wildlife viewing
Conservation of biodiversity	Biodiversity
Carbon sequestration	Climate stability

In addition to these services that are more directly linked to wetland functions, wetlands may also provide cultural and aesthetic values for humans, for example through increased open space and natural viewscapes.

Mitsch *et al.* (2009) identify the following five key categories of wetland ecosystem services. These categories align closely with the wetland functions described above.

- **Climate stability:** Wetlands are particularly important ecosystems with respect to storing carbon, accounting for around 30 percent of all organic carbon storage on the planet. In addition, wetlands are important ecosystems for sequestering carbon from the atmosphere and storing that carbon in plants, detritus, and soils.[3] Humans benefit from this service in the form of decreased damages associated with climate change, for example, to human health, crops, and coastal environments.
- **Water quality improvement:** Wetlands can change water chemistry, removing pollutants such as nitrogen and phosphorus, and increasing water clarity.[4] Multiple benefits of water quality improvements to humans include drinking water supply, improved conditions for fishing and other water-based recreation, and aesthetic values.

[3] Mitsch, William J., James G. Gosselink, Christopher J. Anderson, and Li Zhang. Wetland Ecosystems. Hoboken, NJ: John Wiley and Sons, Inc., 2009. Pg. 13.

[4] *Ibid.* Pg. 15.

- **Flood mitigation:** Wetlands act as sponges, capturing overflow from flooded rivers and streams. The development of floodplains into land uses such as agriculture and residential and commercial development has resulted in costly flood events due to the decreased capability of the landscape to absorb excess water.[5] As with coastal protection, the costs of flooding may be valued in terms of increased damages, or associated decreased property values.
- **Coastal protection:** Recent studies on tsunami and hurricane events have demonstrated the importance of coastal wetlands in attenuating coastal storm surges.[6] By detaining storm-related surges along the coast, wetlands may decrease the extent of damage associated with flooding to infrastructure or other land uses, such as agriculture.
- **Wildlife protection:** Wetlands are important for wildlife in directly providing habitat for species (for example, for breeding, nesting, or feeding), and by supporting food chains by providing habitat for prey species.[7] Due to the diversity of species (waterfowl, other birds, fish, shellfish, reptiles, amphibians) that rely on wetlands to support life functions, these ecosystems are also important in preserving biodiversity. The ways in which wildlife contributes to human well-being are manifold: as food sources, for recreational opportunities (wildlife-viewing, hunting, fishing), and cultural importance. These values may be associated with individual species or with the biodiversity protected by these habitats, in general.

These categories of wetland ecosystem service are the focus of our analysis.

1.1.2 VALUING ECOSYSTEM SERVICES

The value that human populations derive from some categories of ecosystem services may be readily revealed through markets, or through decisions related to individuals' allocation of time and money. For example, expenditures or travel time devoted to such activities as hunting or fishing are indicative of an individual's willingness to pay for the service. The values of other services are more difficult to discern. For example, populations may express positive willingness-to-pay for biodiversity but this value may not be expressed through their spending or other observable behaviors (i.e., non-use values).

The fields of environmental and resource economics have focused on valuing individual services for which data and methods exist to establish quantitative values, such as recreational fishing. Absent quantitative information, other potentially valuable services are often not incorporated into land and resource management decisions. From an economic perspective, this leads to inefficient programs and policies that do not maximize the value of goods and services provided by the landscape.

Over the last 15 years or so, decision-makers have placed increasing focus on valuing ecosystem services holistically to capture as complete an accounting as possible of ecosystem service values and improve decision-making. A seminal study in 1997 (Costanza *et al.*, 1997) generated substantial debate regarding the appropriate way to apply economic information in valuing ecosystem services.

---

5 *Ibid.*, Pg. 16.

6 *Ibid.*

7 *Ibid.*

The study applied an acreage-based, unit value transfer using values from existing studies to establish a total value of services provided by ecosystems across the globe. This resulted in an estimated $33 trillion value of the earth's ecosystems. Of this, the study estimated that global wetlands contributed $4.9 billion annually.[8] A more recent study developed by a subset of these researchers for the New Jersey Department of Environmental Protection (NJDEP, 2007) estimated the value of New Jersey's ecosystem services at $856 billion, of which wetlands contributed the greatest values.[9]

Multiple responses to these studies have argued the theoretical and practical problems associated with scaling up estimates of values taken from other studies of ecosystem services (e.g., Bockstael *et al*., 2000).[10] Such rebuttals argue that this scaling approach is incompatible with economic theory as it implicitly ignores budget constraints, *net* changes in values (i.e., allowing for some level of offsetting values in services where ecosystems are degraded or converted to other land uses as opposed to completely lost), and differences in values for services at the margin (i.e., values per unit are not even but a function of scarcity).

In recent years, multiple efforts have contemplated the appropriate framework for incorporating ecosystem service values in land and resource programs and policies. The Millennium Ecosystem Assessment, for example, was coordinated by the United Nations Environment Programme with the objective of assessing "…the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being."[11]

In addition, the USEPA convened a subcommittee of its Science Advisory Board (SAB), the Committee on Valuing the Protection of Ecological Systems and Services (CVPESS), charged with assessing the Agency's needs, identifying the state-of-the-art and science, and identifying key areas for research with respect to ecosystem service valuation. The CVPESS report emphasized the need for ecologists and economists to work collaboratively to develop methods and models, providing the following three key recommendations and specific advice on how to implement them:

1. Identify early in the valuation process the ecological responses that are likely to be of greatest importance to people and focus the valuation effort on these responses.
2. Predict ecological responses in terms that are relevant to valuation by focusing on the effects of decisions on ecosystem services that are of direct concern to people.
3. Consider the use of a wide range of possible valuation methods to better capture the full range of contributions stemming from ecosystem protection.[12]

---

[8] Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. O'Neill, J. Paruelo, R. Raskin, P. Sutton and M. van den Belt. " The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387 (1997): 253-260.

[9] New Jersey Department of Environmental Protection. Valuing New Jersey's Natural Capital: An Assessment of the Economic Value of the State's Natural Resources. April, 2007.

[10] Bockstael, N., A.M. Freeman, R. Kopp, P. Portney and V.K. Smith. "On Measuring Economic Values for Nature." *Environmental Science and Technology* 34 (8) (2000): 1384-1389.

[11] Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Synthesis*. Island Press: Washington, DC.

[12] U.S. Environmental Protection Agency Science Advisory Board, Committee on Valuing the Protection of Ecological Systems and Services. Valuing the Protection of Ecological Systems and Services: A Report of the EPA Science Advisory Board. May 2009. EPA-SAB-09-012.

Our analysis draws on the guidance provided in the SAB report to ensure that our approach is consistent with other, recent Federal and State efforts to incorporate ecosystem services in decision-making.

The Millennium Ecosystem Assessment and SAB reports agree on the need for ecologists and economists to work together to develop new models that can incorporate site-specific biophysical and economic data to best evaluate how land use and resource management affect the values provided by landscapes. As described in the following discussion, our analysis applies one such tool, the Integration Valuation of Ecosystem Services and Tradeoffs (InVEST).

1.2 FRAMEWORK FOR THE ANALYSIS

This section focuses on two aspects of the framework for our analysis: first, the conceptual approach to valuation through our application of the InVEST tool and, second, the baseline and future scenarios for which we value the change in ecosystem services associated with wetland losses in Delaware.

1.2.1 DESCRIPTION OF THE INVEST TOOL

The InVEST tool was developed by ecologists and economists at The Natural Capital Project, a collaboration of the Woods Institute for the Environment at Stanford University, The Nature Conservancy, the World Wildlife Fund, and the Institute on the Environment at the University of Minnesota.[13] The purpose of InVEST is to make transparent tradeoffs in the delivery, distribution, and economic values of ecosystem services associated with alternative land and resource management scenarios. To this end, InVEST incorporates service-specific ecological production functions and economic valuation models. The functions and models employed for each service are separable and are therefore subject to discussion with stakeholders and experts.

InVEST can be viewed as an analytic framework comprising service-specific tools rooted in ecology, hydrology, biochemistry, and economics. It incorporates well-established methods to first quantify (in biophysical terms) and then value (in economic terms) a suite of ecosystem services. Where data are available to support implementation, the InVEST approach to valuing ecosystem services is superior to a unit-based transfer for multiple reasons. The specific strengths of the InVEST approach are described below.

[13] For more information on The Natural Capital Project and InVEST, see http://www.naturalcapitalproject.org/home04.html.

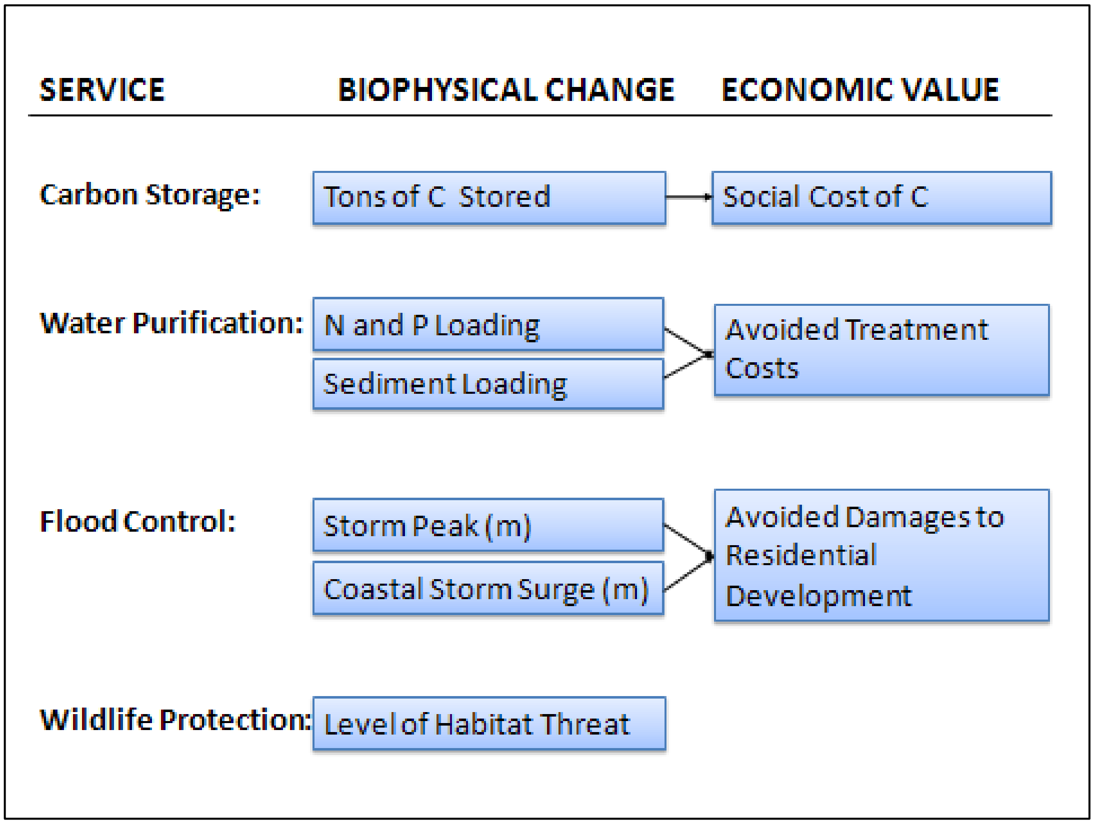
KEY ADVANTAGES OF THE INVEST APPROACH

- Incorporates **spatially-explicit, landscape level** models to account for interactions with surrounding land uses in determining the geographic distribution of services provided across a landscape. This allows users to identify where, for example, wetland conservation efforts should be focused to maximize ecosystem service values.
- Encourages integration of **site-specific data** in estimating the levels of services provided across a given landscape. For example, the extent to which wetlands filter nutrients as they are delivered to waterways is dependent on the wetlands' elevation, nutrient loading of surrounding land uses, vegetation structure, etc.
- Accounts for the **net change in services** associated with land use changes. Where, for example, wetlands are replaced by agricultural developments, the model quantifies the difference in services, such as carbon storage, by the landscape as opposed to assuming a total loss. Quantifying the net change as opposed to the absolute value of services provides more meaningful estimates to inform policy.
- Provides **biophysical and economic endpoints**. In some cases, a biophysical change may provide more information to land managers than economic values of services. In addition, not all services are equally amenable to monetization. InVEST only emphasizes monetization for individual service categories insofar as there exist data and methods consistent with economic theory that are transferable to the site of interest. Otherwise, the InVEST approach advises providing information on changes in terms of biophysical tradeoffs.
- Driven by **policy-relevant scenarios**. The InVEST approach compares the values of services provided by ecosystems according to alternative land and resource management scenarios. These scenarios may be developed with stakeholders and decision-makers to ensure the analysis addresses relevant questions regarding tradeoffs of particular resource management decisions.

For the reasons described above, the InVEST tool is the best available and the state-of-the-science for valuing wetland ecosystem services for Delaware. This approach, which explicitly models the biophysical relationships between wetland resources and associated ecological services, as well as the various attributes that give rise to market and non-market economic values, provides DNREC with more precise and defensible information that may be used in a variety of decision-making contexts.

Exhibit 2 charts the wetland services we evaluate applying the InVEST approach, along with the biophysical and economic endpoints reported. We apply existing models within the InVEST tool for all service categories with the exception of coastal storm surge attenuation. This service will ultimately be included in a version of InVEST devoted to marine and coastal ecosystem services but was not sufficiently developed in time for incorporation in our analysis. Due to the importance of coastal storm protection service provided by wetlands in Delaware, however, we developed a simplified model for use in our analysis following similar principles to the InVEST models. This is described further in Section 4 of this report.

EXHIBIT 2. SERVICES EVALUATED IN THIS ANALYSIS



While we acknowledge the importance of other wetland-related services, such as recreation (e.g., fishing, hunting, and wildlife-view) and commercial fishing and shellfishing, we do not quantify impacts of wetland losses on these services in this analysis. Significant uncertainty exists regarding the effect of our particular wetland loss scenario on species populations, and therefore on the level or quality of associated recreational and commercial activity. As a result, valuation of potential changes in these economic activities is subject to uncertainty sufficient to question the ultimate reliability of results. Our analysis therefore quantifies impacts of wetland losses in terms of the level of habitat degradation, and provides economic information on the value of economic activities (i.e., fishing, hunting, wildlife-viewing) that rely on healthy wetland habitats (Section 5). This economic information is provided as context for the analysis and to demonstrate that wetland habitats within the state contribute positive economic value for citizens, visitors, and the state's economy.

1.2.2 BASELINE AND FUTURE SCENARIOS OF WETLANDS IN DELAWARE

This analysis compares the above categories of value provided by wetlands under the current baseline scenario (existing distribution of wetlands across the state) and a hypothetical future scenario, assuming no changes in wetland conservation or management are implemented over the next 15 years. In effect, this provides DNREC with information regarding potential losses in the above categories of ecosystem services if wetland management continues at the status quo, and land conversion pressure (i.e., development and agriculture) continues over the time frame of the analysis.

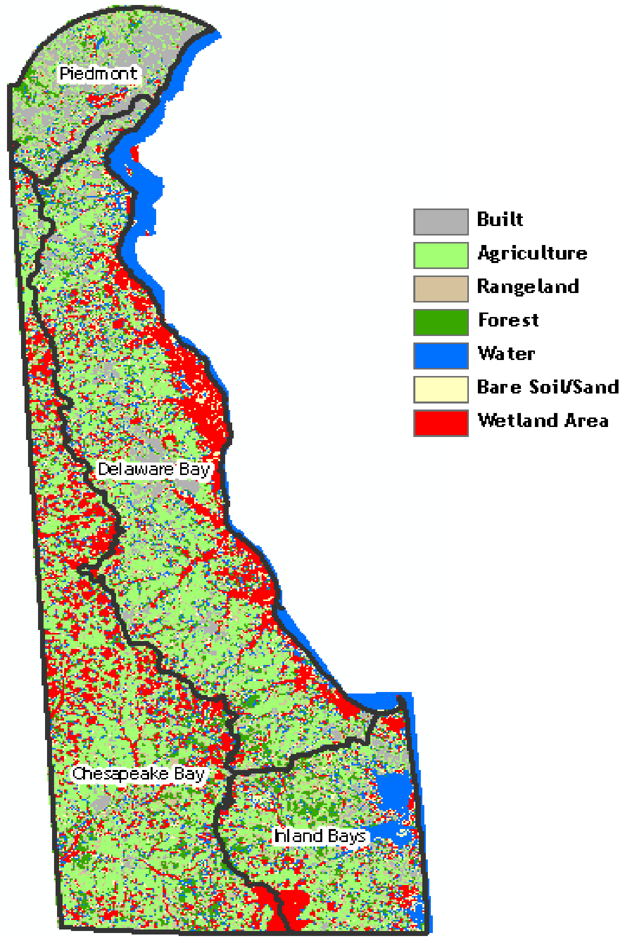
To develop our baseline scenario, we rely on 2007 Land Use/Land Cover (LULC) maps of Delaware made available by the Delaware Geographic Data Committee.[14] We then updated the wetlands within this map with enhanced NWI data provided by DNREC.[15] We aggregated the LULC categories into seven key categories, as described in Exhibit 2. These aggregated LULC categories generally represent the level of detail at which the ecological data are available to inform the models. For example, while the LULC maps identify agricultural lands more specifically by crop type, data regarding the carbon storage capacity are not available at that level of detail. Thus, we aggregate agricultural lands and provide a single value for the amount of carbon stored for modeling purposes. Where data were available to refine the analysis beyond the broad LULC categories, we disaggregated the land use categories to estimate values accordingly. For example, we disaggregated the "built" lands category to identify residential development areas in which houses may be subject to flood damage. Similarly, we disaggregated the wetlands into specific wetland types to assign values to carbon stored in soils.

We converted the LULC shape files into raster format, dividing the landscape by land use into 30 by 30 meter pixels. Our analysis therefore allows for variability in LULC, as well as biophysical and ecological variables such as elevation and precipitation levels, at this geographic scale. As highlighted in Exhibit 3, the scope of our analysis is the entire State of Delaware, divided into the four principle drainages: Piedmont, Delaware Bay, Chesapeake Bay, and Inland Bays.

[14] Sanborn Map Company, Inc. 2007 Delaware Land Use and Land Cover [ESRI Shapefile]. 1st Edition. State of Delaware, Office of Management and Budget, Delaware Geographic Data Committee. 2007.

[15] McGuckin, K. 2011. Methods Used to Create Datasets for the Delaware State Wetlands Update. Conservation Management Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA. Enhanced NWI wetland maps (ESRI Shapefilles) provided by DNREC to IEc in July 2010.

EXHIBIT 3. LULC IN DELAWARE, BASELINE SCENARIO



Data on recent trends in wetland losses informed our future scenario. DNREC provided Geographic Information Systems (GIS) data describing wetland decline by wetland type between 1992 and 2007.[16] We used these data to project continued wetland loss through 2022, considering the rate and location of losses since 1992. Specifically, we relied on the land use change modeler in Idrisi Taiga software to forecast continued trends in wetland loss.[17]

To determine where wetlands are likely to be threatened in the future we considered: 1) the land use to which wetlands were lost in the past (built, agriculture, etc.); and 2) the proximity of those lost wetlands to the land use type that ultimately replaced them. In other words, where, for example, a wetland was converted to development in the past, we measured the distance between the lost wetland and land use threat (i.e., development). This level of proximity to the threat was then used to determine other wetlands across the state that may be similarly threatened by development. Future

[16] Maps comparing wetland distribution between 1992 and 2007 provided to IEc by Kevin McGuckin, Conservation Management Institute, via email on November 8, 2010.

[17] Eastman, J.R., 2009. IDRISI Taiga (Worcester, MA: Clark University).

wetland transitions to other land uses were therefore predicted based on the nature of past transitions. This approach of incorporating distance to various threats is the most common approach to modeling land use changes.

The only changes in the Delaware LULC map between the baseline and future scenario are the forecast wetland losses. We did not model other types of potential land use changes across the state. Thus, the change in services provided between the baseline and future scenarios reflect only the change in services generated by the wetland loss (i.e., transition to other land use).

Exhibit 4 charts the projected wetland transitions between 2007 and 2022. The predominant type of wetland subject to decline is palustrine forested wetlands. These are the most abundant category of wetlands in Delaware. Exhibit 5 describes wetland transitions by drainage. Exhibit 6 summarizes wetland losses by drainage in acres and Exhibit 7 maps the projected wetlands losses across the state.

EXHIBIT 4. FORECAST WETLAND TRANSITIONS IN DELAWARE: 2007-2022

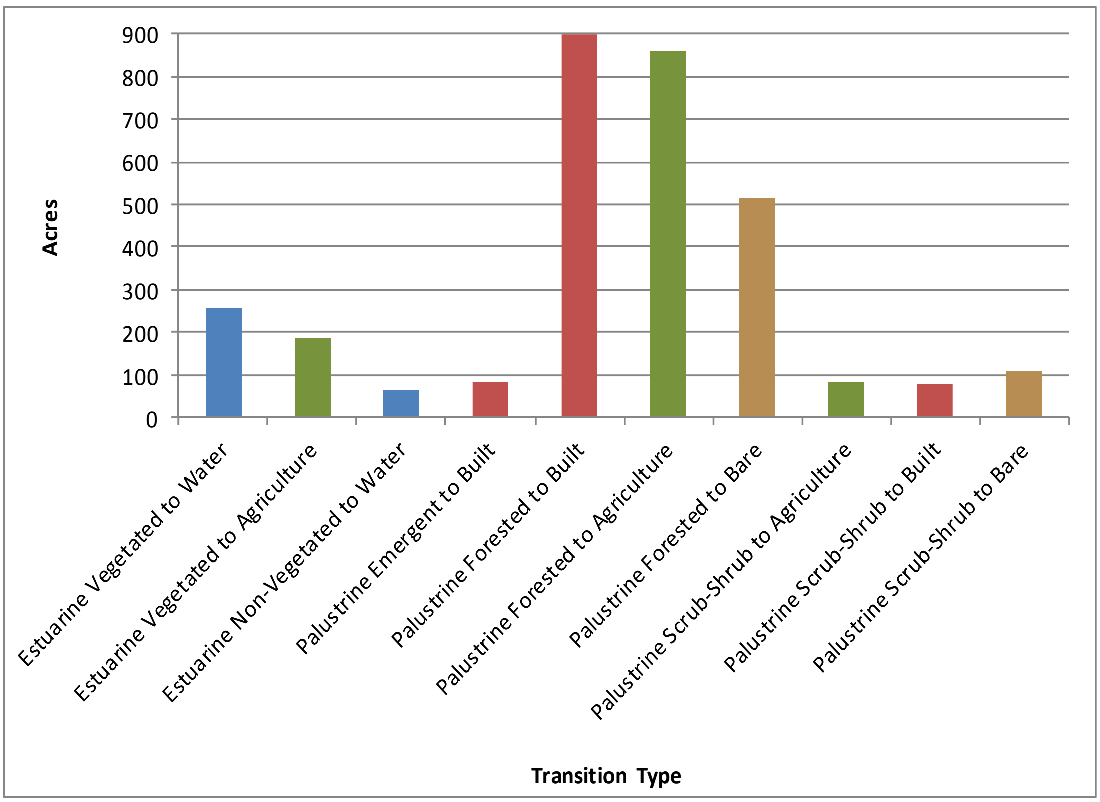


EXHIBIT 5. WETLAND TRANSITIONS BY DRAINAGE: 2007-2022

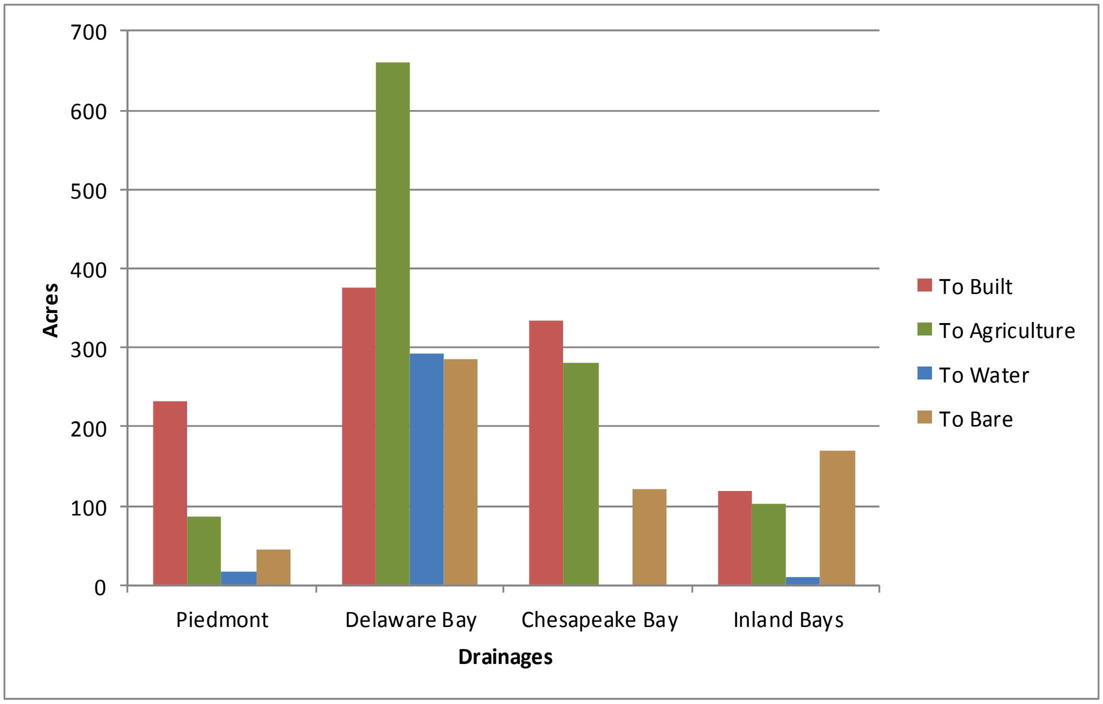
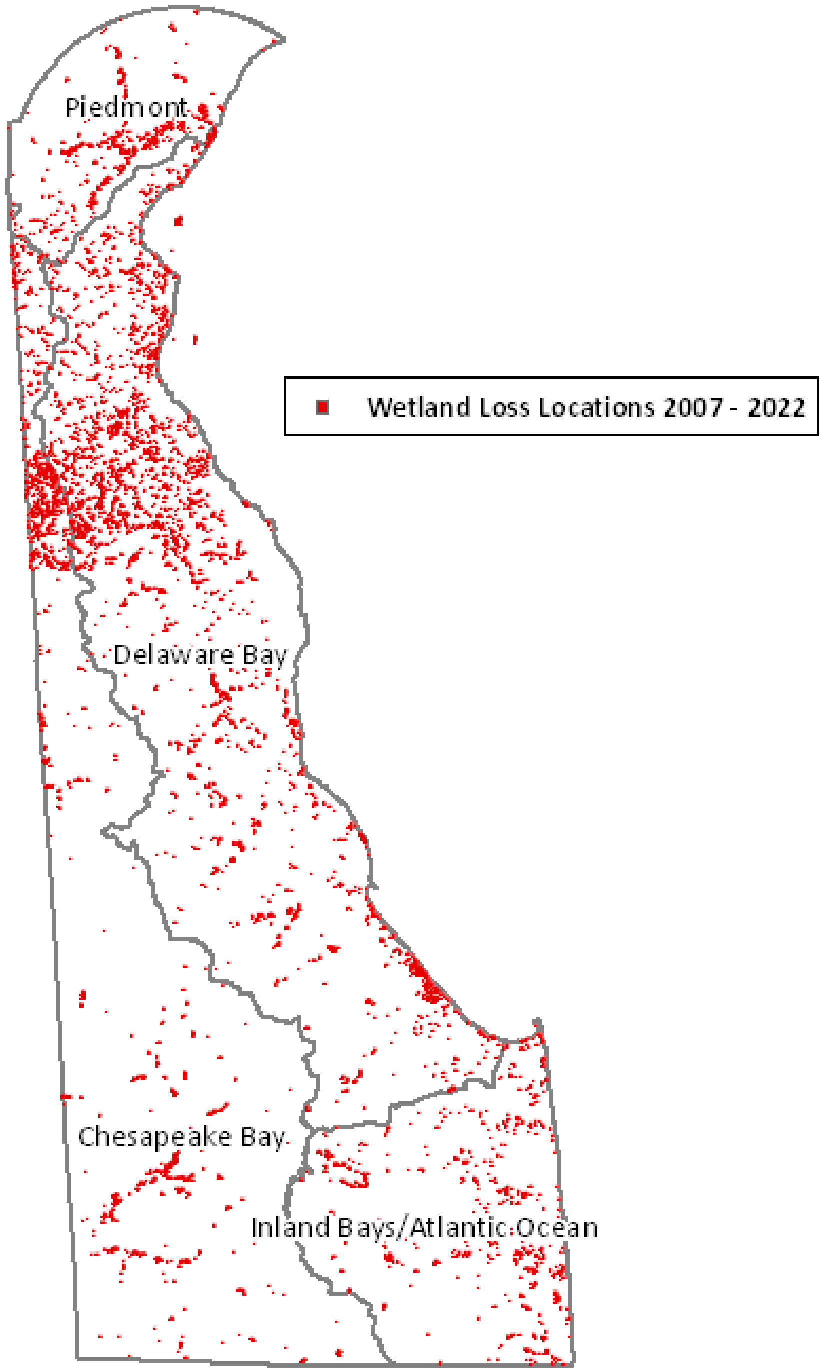


EXHIBIT 6. DISTRIBUTION OF PROJECTED WETLAND LOSSES IN DELAWARE: 2007-2022

DRAINAGE	TO BUILT (acres)	TO AGRICULTURE (acres)	TO WATER (acres)	TO BARE SOIL (acres)	TOTAL LOSS (acres)
Piedmont	232	86	18	45	381
Delaware Bay	376	661	292	286	1,615
Chesapeake Bay	333	280	0	121	734
Inland Bays	118	103	11	170	402
TOTAL STATE	**1,059**	**1,130**	**321**	**622**	**3,132**

EXHIBIT 7. DISTRIBUTION OF PROJECTED WETLAND LOSSES IN DELAWARE: 2007-2022



The change in wetlands between the baseline and future scenarios represent a **1.2 percent decline in wetlands across the state** (3,132 acres of wetland loss) between 2007 and 2022. The changes in values provided by wetland ecosystem services presented in this analysis therefore reflect conversion of 1.2 percent of Delaware wetlands to other LULC categories (primarily development and agriculture). Considering recent trends, these losses derive from realistic assumptions regarding potential future wetland decline within the State.

1.3 SUMMARY OF RESULTS

Our analysis describes the differences in services provided (as described in Exhibit 2) between the baseline and future scenarios. These results are summarized in Exhibit 8 and detailed in Sections 2 through 5 of this report. Importantly, these values are not absolute values of wetlands in Delaware. As described above, they reflect net changes in services provided assuming 1.2 percent of the wetlands is converted to other land uses by 2022.

These results apply an array of data, site-specific where available, to evaluate the following services:

- **Carbon storage (Section 2).** We apply an InVEST model to quantify the difference in carbon storage capacity between the baseline and future scenarios. Economic value is expressed in terms of the social cost of carbon in the atmosphere (i.e., damages associate with climate change).
- **Water purification (Section 3):** We apply InVEST models to calculate the difference in the amount of nitrogen, phosphorus, and sediment retained and exported by the landscape under the baseline and future scenarios. Economic value is expressed in terms of the costs of municipal water treatment to filter nutrients and sediment that would have otherwise been filtered by wetlands.
- **Inland flood control (Section 4):** Our analysis applies an InVEST model at four case study sites across the state to identify the difference in flood heights following a storm event between the baseline and future scenarios. Economic values are expressed in terms of damages of flooding on residential infrastructure.
- **Coastal storm protection (Section 4):** We developed a model to estimate changes in flood heights due to coastal storm surge under the baseline and future scenarios. Economic values are expressed in terms of damages of flooding on residential infrastructure.
- **Wildlife protection (Section 5):** We apply InVEST to model changes in habitat rarity and quality between the baseline and future scenarios, identifying the diversity of species occupying the various habitats. We do not include an economic endpoint for this service due to the difficulty in establishing quantitative relationships between the projected wetland decline and species populations, as previously described. We do, however, provide contextual information on the economic value of ecosystem services associated with healthy habitats in Delaware.

EXHIBIT 8. SUMMARY OF RESULTS ($2010)

SERVICE CATEGORY	BIOPHYSICAL CHANGE ASSOCIATED WITH WETLAND LOSSES	NATURE OF ECONOMIC VALUE	PRESENT VALUE 2007-2022	ANNUALIZED VALUE
Carbon Storage	• 194,417 metric tons of carbon storage lost	Social cost of carbon in the atmosphere (based on damages associated with climate change)	$19,900,000	$1,590,000
Water Purification	• 1.2% increase in nitrogen delivered to waterways • 0.9% increase in phosphorus delivered to waterways • 1.3% increase in sediment delivered to waterways	Municipal water treatment costs	$9,670,000	$770,000
Inland Flood Control*	• Increased flood heights, variable within the case study watershed (see Appendix A)	Damages to flooded residences along Red Clay Creek* Range is due to assumptions regarding number of homes affected and height of homes above ground level	$720 - $21,200*	$57 - $1,690*
Coastal Storm Protection	• Increased flood heights, variable across landscape (see Appendix A)	Damages to flooded residences Range is due to assumptions regarding number of homes affected and height of homes above ground level	$47,600 - $301,000	$3,790 - $23,900
Wildlife Protection	• Direct habitat loss and increased habitat degradation	The biophysical changes reported may affect habitat-related recreational activities such as fishing, hunting, and wildlife-viewing	N/A	N/A

Notes: The present value and annualized value calculations apply a three percent real discount rate. Value estimates are rounded to three significant digits.

* Results are statewide values for all service categories except inland flood control, which represents the results of a case study of Red Clay Creek, as described in Section 4.

It is important to note that the values presented in this report reflect only those service categories described above, and are net values. It is therefore not appropriate to sum these values to estimate a total economic value of wetlands for the following reasons:

- As described above, the values for each service category are net of the values for these services provided by the substitute land use; and
- We do not account for other categories of ecosystem service associated with the wetlands for which data or model limitations prevented reliable valuation, for example, recreation, commercial fishing and shellfishing, as previously noted and described in Section 5.
- We also do not quantify potential cultural values that humans may derive from the wetland ecosystems. Such values are often not expressed through market transaction or observable behavior and quantification requires primary research, for example a survey of the affected population, which is beyond the scope of this analysis.
- In addition, our inland flood analysis includes only the results of case studies within the state for one type of flooding (flooding of floodplain areas around rivers and streams). This leads to an underestimate of the net values provided in this analysis.

On the other hand, we do not consider services provided by land uses that replace the lost wetlands outside of the ecosystem service categories described above. For example, where wetlands are replaced by agriculture, we do not consider offsetting services provided by these agricultural lands (e.g., profits from crops produced), except for the categories considered in this analysis.

In addition to these broad categories of uncertainty, throughout Sections 2 through 5 of this report, we discuss the major sources of uncertainty for each service-specific analysis, qualitatively characterizing the potential magnitude of effect on our results. Exhibit 9 summarizes these uncertainties. We characterize uncertainty as having a "potentially major" effect or a "relatively minor" effect on the results of our analysis. A source of uncertainty with a major effect has the potential to change the conclusions of the analysis. A source of uncertainty with a minor effect may generate relatively small changes in the quantitative results of the analysis but would not likely change the overall conclusions.

EXHIBIT 9. KEY UNCERTAINTIES

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES*
Uncertainties Related To Carbon Storage Analysis		
Estimated social cost of carbon = $118/Mg	**Unknown**: May overestimate or underestimate carbon sequestration values	**Potentially major**. There is a high degree of scatter around the estimated social cost of carbon due to the varying damage estimates associated with climate change. Clearly, there is significant uncertainty regarding how and to what extent climate change may affect human health and the environment. This estimate of the social cost of carbon is likewise subject to that uncertainty. This median estimate, however, represents the best available estimate and stems from a frequently-cited, peer-reviewed economic analysis.
Limited data on some categories of carbon pools	**Unknown**: To the extent that estimates of carbon stored in wetlands are underestimated, this analysis underestimates the effect of the future wetland losses; To the extent that carbon stored in land uses that replace lost wetlands is underestimated, our analysis overstates the effect of future wetland losses.	**Probably minor.** While data regarding carbon pools for particular LULC types are limited, our analysis captures the major carbon pools affected by our baseline and future scenarios of wetland loss in Delaware. That is, data regarding carbon pools in forests and in wetland soils are available to inform our analysis. Refining the carbon pool data for other land use types is unlikely to significantly affect results as those carbon pools are either: a) not associated with LULC types subject to transition according to our scenario; or b) likely to account for much lower levels of carbon storage than the forests and wetland soils that dominate the analysis.
Excluded carbon stored in dead organic matter and harvested wood products	Likely leads to an **underestimate** of the change in value of carbon sequestration	**Probably minor.** While data limitations prevent incorporating these categories of carbon pools, we expect they are relatively minor with respect to the major categories of carbon pools in our analysis.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES*
Assumed static level of carbon stored within a grid cell over time	**Unknown**: May lead to an overestimate or underestimate of values	**Probably minor.** The InVEST model assumes a simplified carbon cycle and does not account for land uses gaining or losing carbon over time. In fact, carbon can move from one pool to another, land uses can become degraded, etc. Due to the relatively short time frame of our analysis, we expect the impacts of this limitation on our analysis are relatively minor. This limitation has major effects on successional land use types, such as harvested forests for which carbon storage may fluctuate greatly over time. This is less likely to be a major issue for the wetland, agricultural, and built land uses that reflect the primary transitions analyzed here.
Uncertainties Related To Water Purification Analysis		
No accounting for chemical or biological interactions besides filtration by ecosystem vegetation and soils	**Unknown.** May overestimate or underestimate treatment costs	**Probably minor.** The model specifically accounts for the capacity of the landscape to filter the pollutants. In fact, other interactions may also diminish the level of pollutant as it flows across the landscape (e.g., interactions with the air, water and other pollutants). To the extent that the pollutant levels are dissipated by other factors before reaching the waterways, this analysis overestimates the level of pollutant loading. However, this overestimation would occur both in our baseline and future scenarios and thus the effect on the difference between the scenarios (which is what we value in this analysis) is likely minor.
Where specific data were not available regarding nutrient and sediment filtering efficiencies, we applied proxies of the most closely matched study in terms of land use type and geographic location	**Unknown.** May overestimate or underestimate treatment costs	**Probably minor.** While the nutrient and sediment filtering efficiency data were limited for some land use types, the estimates we applied were reviewed by the lead hydrologist for the InVEST project, and we anticipate they are reasonable approximations applying the best available data and expert opinion.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES*
Nutrient loading rates are averages for each LULC type for each drainage	**Unknown.** May overestimate or underestimate treatment costs	**Probably minor.** While data were not available on nutrient loading rates for every watershed across the landscape, we applied averages from available field studies data for watersheds in each drainage. While some parcels may vary above or below this average, we anticipate applying the average results in a relatively low error level.
C Factors (crop management factors) are not specific to Delaware lands but were transferred from available studies	**Unknown.** May overestimate or underestimate treatment costs	**Negligible.** Because the costs of sediment treatment are so low compared to nitrogen treatment, the additional sediment loading had a negligible effect on the total present value treatment cost in our analysis. Thus, refinements to the crop management factors are not expected to measurably alter our results.
Absent specific information on soil conservation practices (P Factors), we did not include this variable in the USLE calculations	May **overestimate** treatment costs	**Negligible.** Controlling for soil conservation efforts may reduce our estimate of the amount of additional sediment loading to waterways. The costs of nitrogen removal, however, already overwhelm the costs of sediment removal and, thus, incorporating this factor is not likely to change our results.
Uncertainties Related To Flood Protection Analyses		
We modeled only one type of rainfall event (25-year, 24-hour storm event) using the InVEST storm peak model.	**Underestimates** annual inland flooding levels and damages from storm events.	**Major.** The flood damages calculated for this storm event are additive with any other storm events multiplied by their probabilities of occurring in a given year. While less intense storms may result in fewer or negligible damages, they are likely to occur more often. More intense storms may occur less frequently but would likely result in greater damages.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES*
We apply the InVEST storm peak model to four case study sites.	**Underestimates** annual inland flooding levels and damages from storm events.	**Major.** Of the four case study sites, two experienced measurable changes in flood heights due to wetland losses. While the extent to which wetland losses affect flooding will vary at other sites, it is very likely that other stream segments will also experience increased flooding and associated damages due to the modeled storm events.
The model specifically considers flooding of properties within the floodplain of rivers and streams at the case study sites.	**Underestimates** annual inland flooding levels and damages from storm events.	**Potentially major.** The model considers only one type of potential flooding in focusing on properties within floodplains of streams and rivers. Additional flooding may occur in the form of "ponding" of stormwater in inland areas.
This analysis focuses on damages to residential infrastructure due to inland flooding and coastal inundation.	**Underestimates** annual inland flooding and coastal inundation levels and associated damages.	**Potentially major.** While we focused our analysis where data were available to estimate damages (i.e., we knew where residential development occurs or may occur in the future and approximate damage estimates of flooding to these structures), other development and productive land use may also be affected by increased flooding. For example, commercial and industrial developments may experience damages from flooding. Likewise parks and recreational developments may be affected. These are not captured in our analysis.
Wetland depths are either all zero or all one meter (low and high end assumptions).	**Overestimates** flooding and associated damages.	**Potentially major.** Wetland depths vary by site. We describe results assuming a broad range in wetland depth. According to our zero meter wetland depth assumption, there is no increase in flooding at our four case study sites due to wetland loss. Our damage results for Red Clay Creek therefore reflect a one meter wetland depth assumption. In fact, flooding and associated damages are more likely to be between these scenarios.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES*
The coastal surge model applies a map of flood depth and area due to sea level rise of MHHW plus 1.5 meters as a proxy for the area potentially flooded by a storm surge of MHHW plus 1.5 meters.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** While DNREC's GIS maps of the sea level rise scenario are based solely on elevation and do not take into account any armoring or other flow path dynamics, these are the best data available regarding the potential distribution and levels of coastal inundation.
The coastal surge model assumes land that lies west of the lost wetlands experiences increased flooding (essentially assuming surge travels from east to west).	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** Data are not available to model curvature to reflect how the surge may travel across the landscape. The effect of alternative assumptions (e.g., that the surge travels shore perpendicular) on the results of the analysis are uncertain.
Coastal storm surge analysis applies a wetland surge attenuation rate from Louisiana.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** Absent data on the surge attenuation rates associated with wetlands in Delaware, we apply the best available data. These estimates derive from observations of wetland functioning in Louisiana and their applicability to Delaware is significantly uncertain.
We assume frequency of a 25-year, 24-hour storm event in Delaware is once every 25 years.	May **underestimate** flooding and associated damages.	**Potentially major.** Our assumption is that a 25 year storm event occurs once every 25 years. In fact, it is possible that the frequency of these types of storms in increasing.
At the high end, the analysis assumes full build out of areas zoned for residential development.	May **overestimate** flood damages at the high end.	**Potentially major.** The results of the analysis are sensitive to the estimate of affected houses. The assumption of full build out of these areas at the high end may overestimate the number of houses affected in the future. In fact, development of these areas may become increasingly less attractive due to increasing frequency and intensity of flood events over time.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES*
We assume houses are elevated either 0.30 or 0.61 meters (12 or 24 inches) above ground level, and are not affected by flooding below these levels.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** Foundation heights likely vary across the affected area. Newer homes incorporate newer construction guidance for development in a flood plain and are likely to be relatively elevated. Older homes may be more likely to be constructed close to ground level. To the extent that the average home heights are higher on average than the average estimates assumed, our analysis overestimates potential flood damages.
We assume storm events resulting in surge levels of MHHW plus 1.5 meters occur every ten years.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Probably minor.** The probability of such a storm occurring in a given year is unknown. Based on comparison with FEMA FIS reports (see footnote 53), the ten year estimate reflects a reasonable assumption.
Our damage function is based on national average flood damages for a 2,000 square foot home.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Probably minor.** Home size likely varies within the state and the extent to which the national average damage estimates are applicable to Delaware is uncertain. Relative to the other uncertainties, it is unlikely this assumption has a significant effect on the results of the storm peak analysis.
The model InVEST storm peak model assumes that the rain falls at an even rate during the storm event and falls uniformly across the watershed.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Probably minor.** While rain fall may vary across the landscape, we modeled a relatively targeted area (Red Clay Creek). Relative to the other uncertainties, it is unlikely this assumption has a significant effect on the results of the storm peak analysis.

Uncertainties Related To Wildlife Protection Analysis		
We assume all habitats within a particular habitat type are equally sensitive to a given land use threat.	**Unknown.** May overestimate or underestimate effect on habitat degradation.	**Potentially major.** In assuming all habitat within a particular habitat type is equally sensitive to a given threat, we do not account for potential conservation efforts that may be undertaken at a particular habitat site to protect against or mitigate threats. In the case that conservation efforts are occurring, and are effective, we overstate the effect of our wetland losses on habitat quality at these sites. In addition, habitat that is already significantly degraded may be less resilient than other habitat areas to new threats. In this case, we may underestimate the effect of the wetland loss on habitat quality.
We assume the relative rankings of the sensitivity of each habitat type to various threats described in Exhibit 53.	**Unknown.** May overestimate or underestimate effect on habitat degradation.	**Potentially major.** The relative sensitivity of habitat to the various land use threats is a key input of the analysis. To the extent that these sensitivity estimates do not capture the relative sensitivity of habitat to the various threats, the results of this analysis may change significantly.
We assume the land use threats described in Exhibit 52 are additive in terms of impact on habitat quality.	May **underestimate** overall effect on habitat degradation.	**Potentially major.** It is possible that the combined effects of particular threats on habitat are multiplicative instead of additive. However, our analysis focuses on the relative impact of wetland losses on degradation. Therefore, while this assumption may significantly affect the overall levels of habitat degradation, it is unlikely to significantly change the relative distribution of incrementally degraded habitat.

We account only for land use threats to habitat for which spatial data are available to determine the presence of the threat.	May **underestimate** overall effect on habitat degradation.	**Probably minor.** Habitat threats, such as the spread of invasive species and hydrological alterations are not incorporated into our analysis. While these threats may have a significant impact on habitat quality, our analysis focuses on the incremental effect associated with wetland losses. We present the relative change in habitat quality associated with the wetland losses. Adding additional threats in the analysis would affect the absolute level of habitat quality but is not likely to significantly change the relative distribution of incrementally degraded habitat.
We do not forecast the additional threat to habitat associated with utility, road, and other infrastructure that may accompany the conversion of wetlands to development.	May **underestimate** overall effect on habitat degradation.	**Probably minor.** While the additional threat of additional infrastructure may be an indirect result of the conversion of wetlands to development, one factor in forecasting where wetlands may be converted to development is proximity to existing infrastructure that would support the development. We therefore expect the additional threat to habitat associated with development-related infrastructure to have a relatively minor effect on the overall results of the analysis.
We assume sensitivity of habitat to a given threat decreases exponentially with distance from the threat.	**Unknown.** May overestimate or underestimate effect on habitat degradation.	**Probably minor.** The impact of some threats on habitat quality may decrease linearly with distance or in some other fashion. The results of this analysis, however, are less sensitive to this assumption that to the estimated relative sensitivity of habitats to the various threats.

SECTION 2 | CARBON STORAGE


Photo from DNREC website

Ecosystems such as wetlands contribute to climate regulation by storing carbon in biomass (e.g., vegetation and soils). Wetland soils are particularly efficient at storing carbon. Of the total carbon stored in the earth's soils, experts estimate between 20 and 30 percent is stored in wetland soils.[18] In addition to soil storage, forested wetlands support substantial storage capacity in aboveground biomass, such as trees. As described in Section 1.2.2, forested wetlands are subject to the greatest levels of decline of the Delaware wetland ecosystems. Where wetlands are degraded or replaced by other LULC types, such as residential and commercial development, the stored carbon is released into the atmosphere as greenhouses gases, which contribute to climate change.

2.1 DESCRIPTION OF THE MODEL

The purpose of the carbon model in InVEST is to quantify and value the carbon storage capacity of a landscape by applying information on carbon pools for various LULC types, and the social costs of carbon in the atmosphere. By extension, we can apply the model to estimate the *change* in storage capacity associated with a change in the landscape: in this case, the decline in wetlands between our baseline and future scenarios.

The carbon model is the most straightforward application of the InVEST tool, requiring few inputs relative to the other services. However, the carbon pool data required by the model are limited. While the carbon storage capacity of various forest types has been intensely researched, the same is not true for multiple other land cover types, including wetlands. We therefore conducted a literature review to identify the best available information on carbon pools by LULC type. We were able to identify data describing carbon storage for the most significant carbon pools within the landscape: those contained in forest ecosystems (above and belowground biomass) and in soils across land use

[18] Mitsch, William J. and James G. Gosselink. Wetlands. Fourth Edition. Hoboken, NJ: John Wiley and Sons, Inc., 2007.

types in Delaware. For other types of carbon pools, we detail our assumptions in Section 2.2, and the potential effects of the data limitations on the results of our analysis in Section 2.4.

To quantify the economic value of carbon sequestration, we apply an estimate of the social cost of carbon in the atmosphere. In other words, the value of a Mg of carbon sequestered is equivalent the avoided damage generated by that Mg of carbon if it were released into the atmosphere. Significant uncertainty surrounds the estimate of the social cost of carbon as described in Section 2.4. We therefore compare our results to alternative measures of the cost of carbon in Section 2.3.

2.2 BIOPHYSICAL CHANGE

We relied on review of available literature to identify carbon storage in megagrams (Mg, a megagram is equivalent to one metric ton) per hectare for each LULC type for two types of carbon pools: carbon contained in aboveground biomass and belowground biomass. We also incorporate carbon storage in soils (soil organic carbon) as reported by the U.S. Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS) as part of its Soil Survey Geographic Database (SSURGO). The SSURGO data are developed through national scale U.S. Geological Survey (USGS) soil surveys that have occurred over the past 30 years. USGS samples soil to measure multiple parameters, including soil organic carbon (SOC). The data are used to inform a map of SOC across the United States by interpolating levels between the sampled sites. For this analysis, we overlay the SOC map with our LULC map to derive average estimates of SOC for each land use type in Delaware (Exhibit 10).[19]

The three carbon pools are aggregated for each 30 by 30 meter pixel across the landscape to estimate the Mg of carbon stored per grid cell.[20] Exhibit 10 summarizes the carbon pool data applied in our analysis. Where multiple estimates were available for carbon pools in particular categories, we apply a mean of the values in our analysis. Exhibit 10 also indicates where site-specific data are applied.

[19] SSURGO data provided by Norman Bliss (Principal Scientist, ASRC Research and Technology Solutions, Contractor to the USGS Earth Resources Observation and Science Center) to Derric Pennington (Research Associate, Natural Capital Project) in December 2010. Zonal statistics of SOC estimates for Delaware completed by Derric Pennington, Research Associate, Natural Capital Project, and provided to IEc on March 17, 2011. SSURGO data description included in: Bliss, N.B., Waltman, S.W., and West, L., 2009, Detailed mapping of soil organic carbon stocks in the United States using SSURGO [abs.], in Fall Meeting, San Francisco, CA, Dec. 14-18, 2009, Eos Transactions, Suppl., v. 90, no. 52: Washington, D.C., American Geophysical Union, p. B51F-0367.

[20] The InVEST model also allows for inclusion of carbon contained in dead organic matter and harvested wood products. We did not include these categories in our analysis, however, due to a dearth of data on these carbon pools.

EXHIBIT 10. CARBON POOLS BY LULC TYPE

LULC TYPE	ABOVEGROUND CARBON (Mg/HECTARE)	BELOWGROUND CARBON (Mg/HECTARE)	SOIL CARBON (Mg/HECTARE)
Built	0[b]	0[b]	**39**[a]
Agriculture	10[c]	5[c]	**55**[a]
Rangeland	3[d,e]	2[d]	**73**[a]
Forest	**75**[f]	**15**[f]	**60**[a]
Water	0[b]	0[b]	**0**[b]
Bare Soil/Sand	0[b]	0[b]	**41**[a]
Non-Vegetated Estuarine Wetlands	**3**[g]	**4**[g]	**158**[a]
Vegetated Estuarine Wetlands	**3**[g]	**4**[g]	**99**[a]
Palustrine Aquatic Bed Wetland	20[h]	**	**61**[a]
Palustrine Emergent Wetlands	20[h]	**	**104**[a]
Palustrine Forested Wetlands	**75**[i]	**15**[i]	**126**[a]
Palustrine Scrub-Shrub	20[h]	**	**149**[a]

Notes:

Bolded entries in red font indicate that the data applied are specific to Delaware ecosystems. Other entries employ generic data by LULC type.

** Carbon storage value reported in aboveground biomass value is inclusive of both above- and belowground biomass

Sources:

[a] U.S. Department of Agriculture, SSURGO data provided by Norman Bliss (Principal Scientist, ASRC Research and Technology Solutions, Contractor to the USGS Earth Resources Observation and Science Center) to Derric Pennington (Research Associate, Natural Capital Project) in December 2010. Zonal statistics of SOC estimates for Delaware completed by Derric Pennington, Research Associate, Natural Capital Project, and provided to IEc on March 17, 2011. SSURGO data description included in: Bliss, N.B., Waltman, S.W., and West, L., 2009, Detailed mapping of soil organic carbon stocks in the United States using SSURGO [abs.], in Fall Meeting, San Francisco, CA, Dec. 14-18, 2009, Eos Transactions, Suppl., v. 90, no. 52: Washington, D.C., American Geophysical Union, p. B51F-0367.

[b] We assume a carbon storage value zero for above- and below-ground biomass on non-vegetated land use types.

[c] Absent specific information of carbon storage, we assume the value is between rangeland and forest, closer to rangeland.

[d] Cleary, Pendall, and Ewers. "Aboveground and Belowground Carbon Pools After Fire in Mountain Sagebrush Steppe." *Rangeland Ecology & Management* 63(2) (2010):187-196.

[e] Bolstad and Vose. "Forest and Pasture Carbon Pools and Soil Respiration in the Southern Appalachian Mountains." Forest Science 51(4) (2005): 372-383.

[f] USDA Forest Service. Forest Inventory Data Online. "Aboveground Carbon Storage of Forests in Delaware," "Belowground Carbon Storage of Forests in Delaware," and "Total Area of Forests in Delaware." Accessed September 22, 2010 at http://fiatools.fs.fed.us/fido/index.html.

[g] Average for all tidal wetlands. Data provided by Tracy Elsey-Quirk to IEc on March 16, 2011. The data are associated with the following publication but not specifically reported: Elsey-Quirk, Tracy, Denise M. Seliskar, Christopher K. Sommerfield, and John L. Gallagher. "Salt Marsh Carbon Pool Distribution in a Mid-Atlantic Lagoon, USA: Sea Level Rise Implications." Wetlands (2011) 31: 87-99.

[h] Average value for non-forested wetlands biomass carbon density described in: Bridgham, Scott D., J. Patrick Megonigal, Jason K. Keller, Norman B. Bliss, and Carl Trettin. "The Carbon Balance of North American Wetlands." Wetlands. Volume 26 No. 4, December 2006. pp. 889-916.

[i] We assume carbon storage value for forested wetlands above- and belowground biomass is similar to that of forests in Delaware.

Despite the importance of wetlands in global carbon storage, limited quantitative research exists regarding the specific contribution of wetlands. The existing research on carbon storage in wetlands focuses on soil organic carbon, which is the most significant carbon pool in most wetlands (as identified by the SSURGO data provided in Exhibit 10). Other LULC types were subject to similar limitations regarding data availability. This analysis therefore necessarily makes assumptions regarding carbon storage capacities, as follows:

Aboveground Biomass C Storage

- We assume the amount of carbon stored in aboveground biomass for non- and minimally-vegetated LULC types (built, open water, and bare soil and sand) are negligible.
- We estimate carbon stored in aboveground biomass on agricultural lands is greater than for rangeland but significantly less than forests.
- We assume forested wetlands account for similar levels of aboveground biomass carbon storage to forest ecosystems in Delaware.
- For non-estuarine and non-forested wetland types (i.e., palustrine emergent, aquatic bed, and scrub shrub), we assume the level of aboveground carbon storage is similar to the average value for non-forested wetlands biomass carbon density in North America.

Belowground Biomass C Storage

- We assume the amount of carbon stored in belowground biomass for non- and minimally-vegetated LULC types (built, open water and bare soil and sand) are negligible.
- We assume belowground storage of carbon by palustrine scrub-shrub wetlands is similar to that of rangeland ecosystems.

Soil C Storage

- We assume the amount of carbon stored in soils for open water is negligible.

As noted above, while significant data limitations exist, particularly with respect to carbon storage within aboveground biomass, the available data do capture the major carbon pools within the Delaware landscape: forest ecosystems (included forested wetlands), and wetland soils. The other carbon pool categories reflect relatively small levels of carbon stored. In addition, the major carbon pools affected by our land use change analysis (forested and other wetlands converted primarily to agriculture and built lands), are captured in the existing literature. Thus, we anticipate the effects of the assumptions described above on the results of our analysis are relatively minor.

Exhibit 11 presents the results of the analysis in terms of the net change in carbon stored by drainage across the state of Delaware. Overall, the wetland losses between 2007 and 2022 results in a decrease in carbon storage in Delaware of 194,417 Mg. The greatest losses are associated with wetland transitions in Delaware Bay. The Delaware Bay drainage is subject to a significant level of wetland loss overall, including significant levels of forest wetland losses. Forest wetlands account for the greatest level of carbon storage, as described in Exhibit 10.

EXHIBIT 11. CHANGE IN DELAWARE CARBON STORAGE: 2007-2022

DRAINAGE	ACRES OF WETLANDS LOST	TOTAL CARBON STORAGE LOST: 2007-2022 (Mg)
Piedmont	381	23,275
Delaware Bay	1,615	99,314
Chesapeake Bay	734	47,669
Inland Bays	402	24,159
Statewide	**3,132**	**194,417**

The per acre estimate of carbon storage lost is not even across drainages. This is because the carbon storage loss does not reflect the absolute value of losses in carbon stored in the landscape, but the net loss associated with our specific wetland transition future scenario. That is, the forecast biophysical change in carbon stored within each drainage represents the lost storage capacity of the grid cells for which wetlands were converted to development, agriculture, etc.

2.3 ECONOMIC VALUE

On the valuation side, we apply a per Mg estimate of the social cost of carbon to value the change in carbon sequestration. The social cost of carbon in this case is the median value from existing studies summarized in Tol (2009): **$118 per Mg of carbon** ($2010). This estimate reflects the marginal economic effects of CO_2 emissions and derives from multiple studies researching the welfare effects of climate change in terms of crop damage, coastal protection costs, land value changes, and human health effects.[21]

To estimate the present value of the change in carbon sequestered over time, we assumed linear losses in carbon sequestration over the timeframe of the analysis. In effect, this assumes that wetlands are lost at an even rate between 2007 and 2022, with the full statewide loss in carbon storage of 194,417 occurring by 2022. We then multiply the annual carbon losses by the per unit cost estimate and apply a three percent social discount rate to quantify the present value of these losses.[22] Exhibit 12 provides the economic value of the lost carbon sequestration by drainage.

[21] Toll, Richard S.J. "The Economic Effects of Climate Change." *Journal of Economic Perspectives* 23:2 (2009): 29-51.

[22] For each service-specific analysis, we present economic impacts incurred over time in present value terms. The present value represents the value of a cost or benefit or stream of costs or benefits in common dollar terms. That is, it is the sum of a series of past or future cash flows expressed in today's dollars. We apply a three percent discount rate to calculate the present value impacts, a common social discount rate applied by economists.

EXHIBIT 12. ECONOMIC VALUE OF CHANGE IN DELAWARE CARBON SEQUESTRATION: 2007-2022 ($118/Mg)

DRAINAGE	WETLAND ACRES LOST	VALUE OF LOSS IN CARBON SEQUESTRATION: 2007-2022 (PV, 3% DISCOUNT RATE)
Piedmont	381	$2,390,000
Delaware Bay	1,615	$10,200,000
Chesapeake Bay	734	$4,890,000
Inland Bays	402	$2,480,000
Statewide	**3,132**	**$19,900,000**
Notes: Value estimates are rounded to three significant digits and may not sum due to rounding error.		

Considerable uncertainty exists with respect to the effects of climate change, the magnitude of associated damages, and the appropriate discount rate to apply in damage calculations. Thus, there exists a high degree of scatter around the unit value of carbon sequestered, and the estimated cost of carbon applied in this analysis is subject to uncertainty. We believe that the Tol study, often cited in economics literature, represents the best available information regarding the social cost of carbon. However, we tested the sensitivity of our results to the carbon value assumption by applying an alternative estimate. Our alternative results, provided in Exhibit 13, rely on the market price of carbon dioxide emissions from the European Climate Exchange. As of January 2011, the European Climate Exchange prices were $79 per metric ton of carbon.[23]

EXHIBIT 13. ALTERNATIVE ECONOMIC VALUE OF CHANGE IN DELAWARE CARBON STORAGE: 2007-2022 ($79/Mg)

DRAINAGE	WETLAND ACRES LOST	ALTERNATIVE VALUE OF LOSS IN TOTAL CARBON STORAGE LOST: 2007-2022 (PV, 3% DISCOUNT RATE)
Piedmont	381	$1,600,000
Delaware Bay	1,615	$6,820,000
Chesapeake Bay	734	$3,270,000
Inland Bays	402	$1,660,000
Statewide	**3,132**	**$13,310,000**
Notes: Value estimates are rounded to three significant digits and may not sum due to rounding error.		

An additional measure is the price of carbon paid by the Regional Greenhouse Gas Initiative (RGGI), a market-based program of 11 participating states in the U.S., including Delaware, focused on

[23] The estimate of the price per metric ton of carbon is derived from the price of an entitlement to emit one ton of carbon dioxide. Based on prices of entitlements in January 2011 published at: https://www.theice.com/marketdata/reports/ReportCenter.shtml.

reducing greenhouse gas emissions. In the most recent (March 2011) auction, the price per Mg of carbon was $7.64.[24] Applying this as an estimate of the value per Mg of carbon results in an estimated $1.29 million in lost carbon storage due to the wetland losses, a significantly lower estimate than those reported in Exhibits 12 and 13.

The social cost of carbon is recognized as the appropriate means by which to value incremental changes in carbon storage capacity; that is, the expected damage avoided by an additional ton of carbon stored. We therefore put forward the results from Exhibit 12 (applying estimates of the social cost of carbon as opposed to the market price of carbon) as our best estimate. While market prices for carbon permits (e.g. such as the European Climate Exchange, RGGI, and the now defunct Chicago Climate Exchange) exist, these prices reflect relative regulatory stringency and abatement costs rather than the actual benefits to society of reducing emissions.

Importantly, the values presented above do not translate into a simple cost per acre of wetland lost. As described above, this is because the change in value associated with a given acre of wetland converted is dependent on the new land cover of the lost wetland. For example, where forested wetlands are developed there is a greater loss in carbon sequestered than where tidal wetlands are converted to agriculture.

2.4 KEY UNCERTAINTIES

Exhibit 14 summarizes the key uncertainties associated with the carbon storage analysis. These uncertainties are ranking in terms of their significance with respect to the results of this analysis. The most significant source of uncertainty in this analysis is the economic value estimate for carbon sequestered by ecosystems.

[24] Clearing price per allowance (equivalent to a short ton) of CO2 was $1.89. Converting to Mg of carbon, the price is $7.64. Source: Potomac Economics. March 2011. "Market Monitor Report for Auction 11." Prepared for RGGI, Inc.

EXHIBIT 14. KEY UNCERTAINTIES OF THE CARBON STORAGE ANALYSIS

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES
Estimated social cost of carbon = $118/Mg	**Unknown**: May overestimate or underestimate carbon sequestration values	**Potentially major**. There is a high degree of scatter around the estimated social cost of carbon due to the varying damage estimates associated with climate change. Clearly, there is significant uncertainty regarding how and to what extent climate change may affect human health and the environment. This estimate of the social cost of carbon is likewise subject to that uncertainty. This median estimate, however, represents the best available estimate and stems from a frequently-cited, peer-reviewed economic analysis.
Limited data on some categories of carbon pools	**Unknown**: To the extent that estimates of carbon stored in wetlands are underestimated, this analysis underestimates the effect of the future wetland losses; To the extent that carbon stored in land uses that replace lost wetlands is underestimated, our analysis overstates the effect of future wetland losses.	**Probably minor.** While data regarding carbon pools for particular LULC types are limited, our analysis captures the major carbon pools affected by our baseline and future scenarios of wetland loss in Delaware. That is, data regarding carbon pools in forests and in wetland soils are available to inform our analysis. Refining the carbon pool data for other land use types is unlikely to significantly affect results as those carbon pools are either: a) not associated with LULC types subject to transition according to our scenario; or b) likely to account for much lower levels of carbon storage than the forests and wetland soils that dominate the analysis.
Excluded carbon stored in dead organic matter and harvested wood products	Likely leads to an **underestimate** of the change in value of carbon sequestration	**Probably minor.** While data limitations prevent incorporating these categories of carbon pools, we expect they are relatively minor with respect to the major categories of carbon pools in our analysis.
Assumed static level of carbon stored within a grid cell over time	**Unknown**: May lead to an overestimate or underestimate of values	**Probably minor.** The InVEST model assumes a simplified carbon cycle and does not account for land uses gaining or losing carbon over time. In fact, carbon can move from one pool to another, land uses can become degraded, etc. Due to the relatively short time frame of our analysis, we expect the impacts of this limitation on our analysis are relatively minor. This limitation has major effects on successional land use types, such as harvested forests for which carbon storage may fluctuate greatly over time. This is less likely to be a major issue for the wetland, agricultural, and built land uses that reflect the primary transitions analyzed here.

SECTION 3 | WATER PURIFICATION

Wetlands can alter water chemistry by impeding flow from developed land, and filtering out nutrients and sediment thereby improving the quality of water downstream of the wetland. Purifying storm water runoff in this manner can provide increased water clarity, as well as improved conditions for municipal drinking water supply and recreational activities, such as boating and fishing.

Photo from DNREC website

3.1 DESCRIPTION OF MODELS

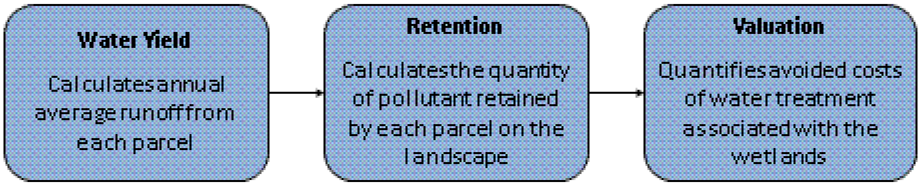
This analysis applies InVEST models to forecast the effect of our future wetland loss scenario on mitigating non-point source pollution in terms of three water quality parameters:

- Nitrogen;
- Phosphorus; and
- Sediment concentrations.

The linked models combine water yield, nutrient loading, and filtration information, to calculate the amount of nutrients and sediment retained and exported to waterways across a given landscape. We calculate the nutrient and sediment retention for each individual 30 by 30 meter pixel. This allows us to determine how our forecast of wetland losses (i.e., transition of wetlands to another land use) affects retention and exportation of these pollutants by the landscape.

There are three major steps to this process and each is subject to significant data requirements: 1) a water yield model calculates annual average runoff from each pixel; 2) retention models apply information on loading and retention by land cover class to determine the quantity of pollutant retained and exported; and 3) the valuation model employs information on per unit costs of water treatment in Delaware to determine the equivalent value of the wetlands in filtering pollutants (Exhibit 15).

EXHIBIT 15. LINKED MODELS FOR WATER PURIFICATION ANALYSIS



The significant data requirements (as described in Section 3.2) subject this analysis to layered uncertainties. Unlike the carbon model, however, much of the data employed by these models are provided by environmental monitoring efforts in Delaware. The analysis of this service therefore better reflects on-the-ground conditions in Delaware, involving relatively little transfer of environmental and economic data from studies at other sites.

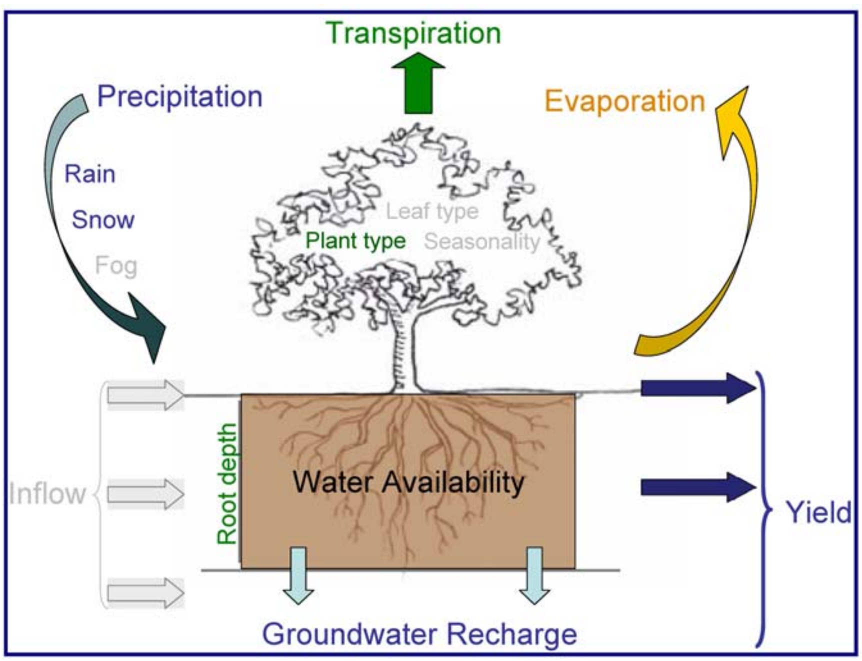
3.2 BIOPHYSICAL CHANGE

This section describes the forecast change in nitrogen, phosphorus, and sediment exported to Delaware waterways in each of the four principal drainages. All data sources are described, highlighting where site-specific data were available to inform the analysis.

3.2.1 WATER YIELD MODEL

The InVEST water yield model first estimates the amount of water running off of each pixel as a function of precipitation and evapotranspiration. Exhibit 16 provides a graphical depiction of the water yield model framework.

EXHIBIT 16. WATER YIELD MODEL CONCEPTUAL FRAMEWORK



Source: The Natural Capital Project. InVEST 1.004 Beta User's Guide: Integrated Valuation of Ecosystem Services and Tradeoffs. Ed: Heather Tallis and Taylor Ricketts. 2009.

The model first determines water yield (Y_{xj}) for each pixel across the landscape according to a simplified water cycle, as follows:[25]

$$Y_{xj} = (1 - (AET_{xj}/P_x)) * P_x$$

Where:

Y_{xj} = Annual water yield for pixel x of land use type j.

AET_{xj} = The annual evapotranspiration on pixel x of land use type j.

P_x = Annual precipitation on pixel x.

The evapotranspiration partition of the water balance, (AET_{xj}/P_x), is an approximation of the Budyko curve developed by Zhang *et al*. (2001), as follows.[26]

$$AET_{xj}/P_x = (1 + \omega_x R_{xj})/(1 + \omega_x R_{xj} + (1/R_{xj})); \text{ where}$$

$$R_{xj} = (k_{xj} * ETO_x)/P_x$$

$$\omega_x = Z * (AWC_x/P_x)$$

$$AWC_x = \min(SDx, RD_{xj}) * PAWC_x$$

In these equations:

ω_x = The ratio of plant accessible water storage in soils to expected precipitation.

R_{xj} = The ratio of reference evapotranspiration to precipitation on pixel c of land use type j (Budyko dryness index).

ETO_x = Reference evapotranspiration from pixel x.

k_{xj} = Plant evapotranspiration coefficient on pixel x of land use type j (used to translate reference to actual evapotranspiration).

Z = The Zhang constant describing seasonal distribution of rainfall.[27]

AWC_x = Volumetric available water content of pixel x.

---

[25] The following discussion of the functions applied in the InVEST water purification model is from: The Natural Capital Project. InVEST 1.004 Beta User's Guide: Integrated Valuation of Ecosystem Services and Tradeoffs. Ed: Heather Tallis and Taylor Ricketts. 2009.

[26] Zhang, L., W.R. Dawes, and G.R. Walker. "Response of mean annual evapotranspiration to vegetation changes at catchment scale." Water Resources Research 37 (2001): 701-708.

[27] This Z constant is assigned a value in the InVEST water yield model based on average annual rainfall (P_x). Within Delaware, P_x varies across the landscape from 900 to 1,240 mm. Where $500 < P_x < 1{,}000$, Z = 1.5. Where $1{,}000 < P_x < 1{,}500$, Z = 3.0.

SD_x = Soil depth of pixel x.

RD_{xj} = Root depth of pixel x of land use type j.

$PAWC_x$ = Plant available water content of pixel x.

These variables are described further in Exhibit 17. The inputs required for the model are a mix of GIS data and LULC specific variables, as described in Exhibit 17. The GIS data are all site-specific information, as mapped in Exhibit 18. Precipitation and reference evapotranspiration data were provided by the Delaware Environmental Observing System (DEOS). We applied the monitored data measured at 22 stations in Delaware to interpolate average annual values for these variables across the state.

The soil depth and plant available water content data are from the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic Database (SSURGO). These variables describe the amount of water held by soil that is available for use by the vegetation.

Data for root depths are not Delaware-specific but apply generally to the LULC types occurring in the state (Exhibit 19). Finally, the evapotranspiration coefficients translate the map of reference evapotranspiration, which is based on a reference vegetation type (alfalfa), to actual evapotranspiration for different vegetation classes (Exhibit 20). This better reflects evapotranspiration levels across the landscape as some vegetation types transpire more than alfalfa (e.g., corn twice as much and deciduous forest four times as much).

EXHIBIT 17. DATA REQUIREMENTS FOR INVEST WATER YIELD MODEL

DATA INPUT	PURPOSE IN MODEL	DATA SOURCE
GIS DATA INPUTS		
Precipitation (P_x)	Estimate of average annual rainfall (mm)	Delaware Environmental Observing System (DEOS), Delaware Environmental Monitoring and Observing Network (DEMON) data for 22 stations for 2008 and 2009*
Reference Evapotranspiration (ETO_x)	Potential loss of water from soil due to evaporation from soil and transpiration of a reference vegetation cover (alfalfa) (mm)	DEOS DEMON data for 22 stations for 2008 and 2009*
Soil Depth (SD_x)	Average soil depth per cell (mm)	U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Soil Survey Geographic Database (SSURGO)*
Plant Available Water Content ($PAWC_x$)	Fraction of water than can be stored in soil profile for plants' use	USDA NRCS SSURGO*
OTHER DATA INPUTS		
Root Depth (RD_{xj})	Maximum root depth for vegetated land use classes (mm)	Canadell, J.; R.B. Jackson; J.R. Ehleringer; H.A. Mooney; O.E. Sala; E.D. Schulze. "Maximum rooting depth of vegetation types at the global scale." *Oceologia* 108 (1996): 583 – 595. (Exhibit 19)

DATA INPUT	PURPOSE IN MODEL	DATA SOURCE
Evapotranspiration Coefficient (k_{xj})	Land use specific factor to translate reference evapotranspiration to actual evapotranspiration	Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. United Nations Food and Agriculture Organization Irrigation and Drainage Paper 56. 1998.** Exhibit 20)

* Site-specific data for Delaware.

** Evapotranspiration estimates for each land use type are from Allen *et al*., 1998; for LULC types not included in Allen *et al*, the estimates applied are based on expert opinion of the InVEST lead hydrologist at Stanford University for application in the analysis, as described in Exhibit 20.

EXHIBIT 18. GIS DATA REQUIREMENTS AND SOURCES FOR WATER YIELD MODEL

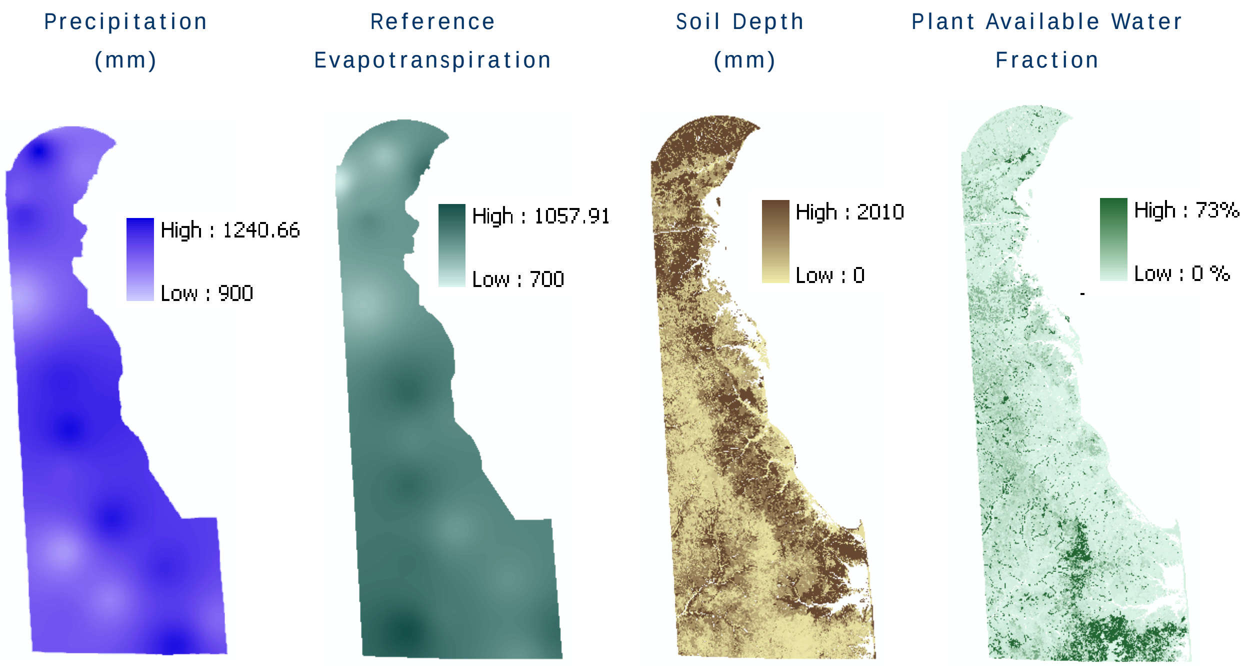


EXHIBIT 19. ROOT DEPTH DATA

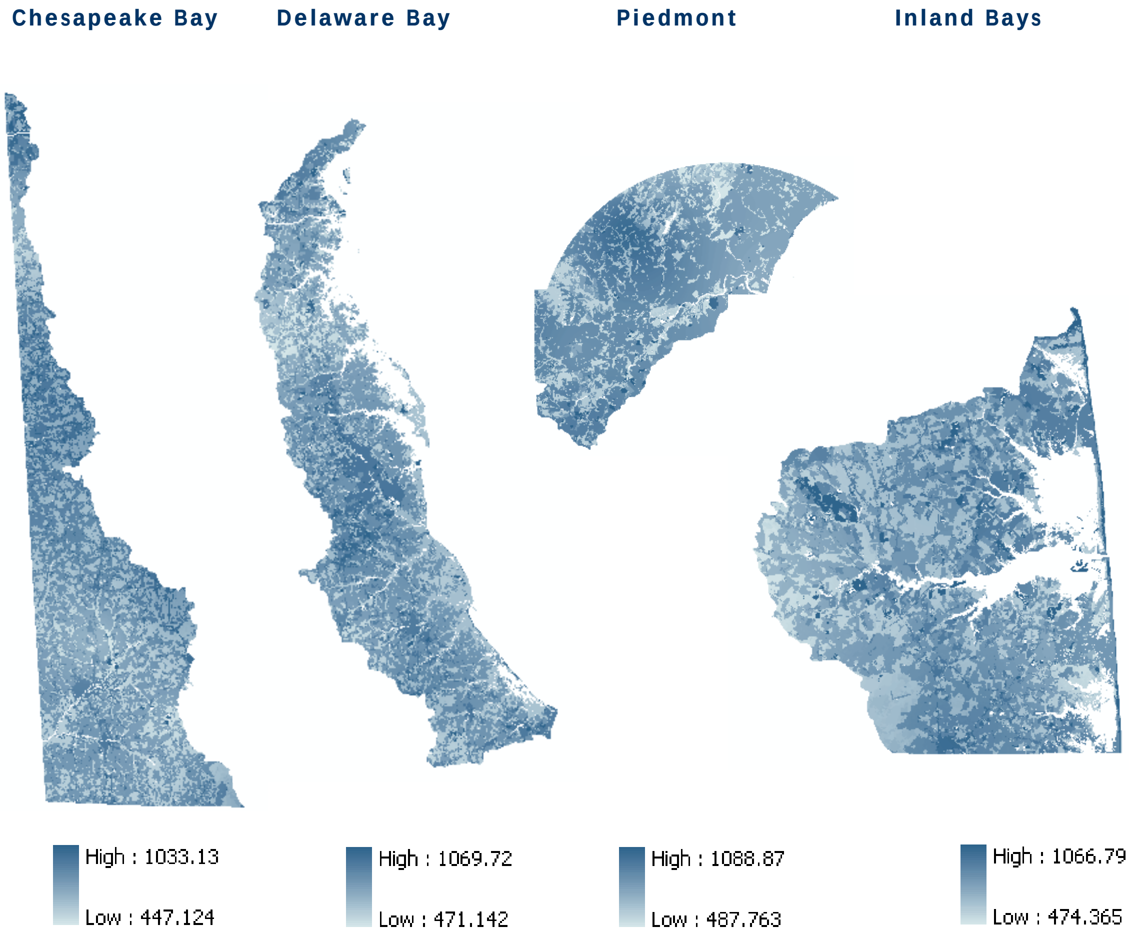
LULC	BASIS FOR ROOT DEPTH ASSUMPTION	ROOT DEPTH (mm)
Built	Non-vegetated land use	N/A
Agriculture	*Zea mays* (corn), Nebrasks	2400
Rangeland	Alluvial loam soil, *Quercus douglasii*, California	3700
Forest	Temperate deciduous forest, *Quercus sp.*, Virginia	4000
Water	Non-vegetated land use	N/A
Bare Sand/Soil	Non-vegetated land use	N/A
Non-Forested Wetlands	Temperate grassland, silt loam soil, Illinois	1600
Forested Wetlands	Temperate deciduous forest, *Quercus sp.*, Virginia	4000
Source: Estimated root depths are based on studies for the LULC and geographic location closest to Delaware described in: Canadell, J.; R.B. Jackson; J.R. Ehleringer; H.A. Mooney; O.E. Sala; E.D. Schulze. "Maximum rooting depth of vegetation types at the global scale." *Oceologia* 108 (1996): 583 – 595.		

EXHIBIT 20. EVAPOTRANSPIRATION COEFFICIENTS

LULC	BASIS FOR EVAPOTRANSPIRATION COEFFICIENT ASSUMPTION	EVAPOTRANSPIRATION COEFFICIENT
Built	Based on discussion with InVEST lead hydrologist, value is between barren land and grassland	0.5
Agriculture	Average for major Delaware crops	0.7
Rangeland	Comparable to grassland	0.7
Forest	Slightly higher than conifer forests described in Allen et al. (Allen *et al.*, 1998 does not consider other forest types)	1.2
Water	Middle of range for water of varying depths	1
Bare Sand/Soil	Value for barren land	0.2
Non-Forested Wetlands	Value for temperate climate wetlands	1.1
Forested Wetlands	Comparable to forest	1.2
Source: Coefficients are based on discussion with InVEST lead hydrologist and information provided in: Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. United Nations Food and Agriculture Organization Irrigation and Drainage Paper 56. 1998.		

Exhibit 21 maps the results of the water yield model for each drainage. The water yield per pixel is a key input for the following model, which applies a digital elevation model (DEM) to describe how the water is then distributed across the landscape towards waterways.

EXHIBIT 21. WATER YIELD MODEL RESULTS (mm/year)



3.2.2 NUTRIENT RETENTION MODEL

The nutrient retention model combines the water yield output with a statewide DEM to model how the water flows the across the landscape as a function of relative elevation. As noted in the InVEST User's Guide, the model is not well-suited for locations subject to extensive tile drainage or ditching as these features re-route water flowing across a landscape. To overcome this limitation, DNREC provided a ditch layer for the State of Delaware. We added this layer to the DEM in order to improve the precision of the model in simulating water flows. As a result of this improvement, water delivered to the ditches is then routed to the stream. In effect, the ditches add an additional stream layer in terms of modeling runoff.

Second, we incorporate data on land use-specific nutrient loading rates derived from field studies in Delaware. Average loading rates by land use type were provided by DNREC for various watersheds across the state. We used these data to calculate average nitrogen and phosphorus loading rates (in kg/ha/year) by LULC type for each pixel within the four principle drainages. As the nitrogen and phosphorus flow across the landscape, we apply information on vegetation filtering capacities to determine the extent to which these nutrients are filtered by the vegetation of the downslope pixels.

For example, consider the outflow quantity of nutrient (NO) from four cells:

CELL	VEGETATION FILTERING VALUE (%)	NUTRIENT LOADING VALUE (KG/HA/YEAR)	NUTRIENT RETAINED BY CELL	NUTRIENT OUTFLOW FROM CELL
1	V_1	N_1	0	N_1
2	V_2	N_2	$NR_2 = N_1 * V_2$	$NO_2 = (N_1 * (1-V_2)) + N_2$
3	V_3	N_3	$NR_3 = NO_2 * V_3$	$NO_3 = (NO_2 * (1-V_3)) + N_3$
4	V_4	N_4	$NR_4 = NO_3 * V_4$	$NO_4 = (NO_3 * (1-V_4)) + N_4$

Ultimately, this allows us to calculate the fraction of nutrients delivered to streams. The InVEST model applied GIS to sum the nutrient outflows from all individual cells to determine the total pollutant loading to streams.

Exhibit 22 describes the source of the data employed in the nutrient retention model, highlighting site-specific information. All of the data for the nutrient retention model are specific to Delaware with the exception of the vegetation filtering values, which were informed by a literature review.

Exhibits 23 and 24 provide the loading rates by LULC and drainage for nitrogen and phosphorus, respectively. The land use responsible for the greatest levels of nutrient loading (primarily nitrogen) is agriculture, followed by developed lands. Thus, conversion of wetlands, which involve relatively low loading rates, to developed or agricultural lands, will increase nutrient loadings across the landscape. The variation in average loading rates for a particular land use across drainages is most likely due to differences in vegetation type and structure (e.g., crop type or condition of forests). Very little variation exists with respect to loading rates for built land across the drainages.

EXHIBIT 22. DATA REQUIREMENTS FOR INVEST NUTRIENT RETENTION MODEL

DATA INPUT	PURPOSE IN MODEL	DATA SOURCE
GIS DATA INPUTS		
Digital Elevation Model (DEM)	Used to model water flow across landscape; DEM is modified to incorporate ditches across the State of Delaware	U.S. Geological Survey (USGS) National Elevation Data, Delaware 1-Arc Second, Series Issue 0.1. Sioux Falls, SD: U.S. Geological Survey, 2002 – 2005.* Institute for Public Administration, Water Resources Agency College of Human Services, Education and Public Policy, University of Delaware. 2008. Development of Hydrogeomorphic Modifiers to the Statewide Wetlands Mapping Project (SWMP) Dataset for Selected Watersheds in the Delaware Estuary, State of Delaware. Summary report for Department of Natural Resources and Environmental Control. 34pp.* Tiner, R.W., H.C. Bergquist, J.Q. Swords, and B.J. McClain. 2001. Watershed-based Wetland Characterization for Delaware's Nanticoke River Watershed: A Preliminary Assessment Report. U.S. Fish & Wildlife Service, National Wetlands Inventory (NWI) Program, Northeast Region, Hadley, MA. Prepared for the Delaware Department of Natural Resources and Environmental Control, Division of Soil and Water Conservation, Dover, DE. NWI technical report. 89 pp. plus 22 maps.*
Water Yield Map	Output from linked InVEST model	InVEST model*
OTHER DATA INPUTS		
Nutrient Loadings (N)	Average loading of nutrients by land use type by drainage (kg/ha/year)	Site-specific loading rates by LULC category for specific watersheds in Delaware provided by DNREC (Exhibits 23 and 24)*
Vegetation Filtering Values (V)	Capacity of a LULC categories to retain the pollutant as a function of the vegetation type	Literature review (Exhibit 25)
* Site-specific data for Delaware.		

EXHIBIT 23. NITROGEN LOADING RATES BY LULC AND DRAINAGE (KG/HA/YEAR)

LULC	DELAWARE BAY	CHESAPEAKE BAY	INLAND BAYS	PIEDMONT
Built	15.8	15.9	16.8	8.3
Agriculture	15.4	21.8	38.4	12.7
Rangeland	11.3	4.9	13.9	8.3
Forest	4.1	4.5	5.6	5.6
Water	2.7	2.7	5.0	5.0
Bare Soil	0	0	0	0
Non-forested wetlands	1.0	0	0	0.3
Forested wetlands	4.1	4.5	5.6	5.6

Notes: Estimates rounded to nearest tenth of a kg/ha/year.
Source: Developed from DNREC nitrogen loadings spreadsheets provided to IEc via email from Lyle Jones on November 30, 2010.

EXHIBIT 24. PHOSPHORUS LOADING RATES BY LULC AND DRAINAGE (KG/HA/YEAR)

LULC	DELAWARE BAY	CHESAPEAKE BAY	INLAND BAYS	PIEDMONT
Built	1.0	1.1	0.5	0.6
Agriculture	1.3	0.9	0.8	1.0
Rangeland	0.5	0.9	0.8	0.6
Forest	0.2	0.2	0.4	0.4
Water	0.2	0.2	0.3	0.3
Bare Soil	0	0	0	0
Non-forested wetlands	0.4	0	0	0.1
Forested wetlands	0.2	0.2	0.4	0.4

Notes: Estimates rounded to nearest tenth of a kg/ha/year.
Source: Developed from DNREC nitrogen loadings spreadsheets provided to IEc via email from Lyle Jones on November 30, 2010.

Exhibit 25 provides the results of our literature review regarding vegetation filtering capacities by LULC type. Data were not available for some LULC types, such as built and sand, as these land uses lack significant vegetation cover to impede flow and retain nutrient and, as such, are subject to less research on the topic. For these land use categories, we consulted the InVEST lead hydrologist and developer of the nutrient retention model, who suggested applying 10 percent retention values to reflect a relatively low capacity for nutrient filtration of relatively non-vegetated lands.

Of note, agriculture and built land uses are not only the primary land uses of concern with respect to nutrient loading, but also relatively inefficient at filtering nutrients. On the opposite end of the spectrum, wetlands contribute low loading and high retention rates.

EXHIBIT 25. VEGETATION FILTERING VALUES BY LULC TYPE

LULC	ASSUMPTION/SOURCE	N (%)	P (%)
Built	Low end for retention per communication with InVEST lead hydrologist and model developer	10	10
Agriculture	Simpson, Thomas and Sarah Weamert. Developing Nitrgoen, Phosphorus and Sediment Reduction Efficiencies for Tributary Strategy Practices. BMP Assessment: Final Report. Report of the University of Maryland, Mid-Atlantic Water Program. March 2009. (Simpson and Weamert, 2009)	38	7
Rangeland	Estimate for grasslands from: Simpson and Weamert, 2009	32	40
Forest	Estimate for forests in the Chesapeake Bay area from: Simpson and Weamert, 2009	45	40
Water	Estimates for "wet ponds" from: Simpson and Weamert, 2009	20	45
Sand/Shoreline	Low end for retention per communication with InVEST lead hydrologist and model developer	10	10
Wetlands	Mean of 5 studies regarding nitrogen retention and 11 studies regarding phosphorus retention of wetlands as described in: Johnston, Carol A. "Sediment and Nutrient Retention by Freshwater Wetlands: Effects on Surface Water Quality." *Critical Reviews in Environmental Science and Technology* Volume 21 (1991): 491-565.	63	45

Results of the nutrient retention model are provided in Exhibit 26. The percentages represent the percent increase in nitrogen and phosphorus loading due to the wetland losses of our future scenario. The relatively modest change in nutrient loading reflects the forecast loss in wetlands (1.2 percent decrease) through 2022. The loss in wetlands results not only in increased loading rates for these nutrients but also decreased filtering capacity of the converted pixels (i.e., to built or agriculture land uses).

EXHIBIT 26. CHANGE IN NUTRIENT RETENTION AS A RESULT OF WETLAND LOSSES: 2007-2022

DRAINAGE	WETLAND ACRES LOST	% CHANGE IN N LOADING	% CHANGE IN P LOADING
Piedmont	381	1.5%	1.2%
Delaware Bay	1,615	1.9%	1.4%
Chesapeake Bay	734	0.8%	0.6%
Inland Bays	402	0.8%	0.4%
STATEWIDE	**3,132**	**1.2%**	**0.9%**

3.2.3 SEDIMENT RETENTION MODEL

Similar in purpose and framework to the nutrient retention model, the InVEST sediment retention model calculates the amount of sediment retained and exported by a landscape as a function of geomorphology, land use, and land management practices. The model is based on the Universal Soil Loss Equation (USLE), a commonly applied sedimentation model, to calculate erosion from a given pixel. We then combine information on the sediment retention efficiencies of downslope land uses to calculate the amount of sediment ultimately reaching the stream. The USLE calculates erosion from a given pixel as follows:

$$USLE = R \times K \times LS \times C \times P$$

Where:

R = Rainfall erosivity.

K = Soil erodibility.

LS = Length slope factor.

C = Crop or vegetation management factor.

P = Conservation practices factor.

Exhibit 27 describes the sources for each of these inputs, highlighting which data are site-specific. The model requires GIS data on elevation (DEM), rainfall erosivity, and soil erodibility. The erosivity is the kinetic energy of rainfall multiplied by the intensity of rain on a given pixel (the "R Factor" in the USLE). The soil erodibility is the susceptibility of soil particles to detachment and transport by rainfall and runoff (the "K Factor" in the USLE). The DEM, along with information on pixel size (30 by 30 meters) determines the Slope Length Factor ("LS Factor") in the model. This may be thought of as, "the distance that a drop of rain/sediment runs until its energy dissipates."[28]

In addition to the GIS data, the USLE incorporates information on the crop or vegetation management factor (the "C Factor"). The C Factor incorporates the relative effectiveness of soil and crop management practices in abating soil loss (as compared to continuously fallow and tilled land). Exhibit 28 provides information on the sources and assumptions applied to estimate C Factor values for each LULC type.

The use of the USLE in InVEST also allows for incorporating information on supporting conservation practices (the "P Factor"), where available. This applies specifically to agricultural land cover and requires information on soil conservation practices across the landscape. Absent information on the distribution of various soil conservation practices across agricultural lands in Delaware, we did not incorporate this factor into our analysis. As described in Section 3.4, we do not anticipate excluding this variable had a measurable effect on our results.

Exhibit 29 provides information on the sediment retention efficiencies by LULC type. As the soil erodes from pixels, this information identifies the fraction of the sediment retained by the vegetation as the runoff travels downslope.

[28] Information on the use of the USLE is provided in: The Natural Capital Project. InVEST 1.004 Beta User's Guide: Integrated Valuation of Ecosystem Services and Tradeoffs. Ed: Heather Tallis and Taylor Ricketts. 2009.

EXHIBIT 27. DATA REQUIREMENTS FOR THE INVEST SEDIMENT RETENTION MODEL

DATA INPUT	PURPOSE IN MODEL	DATA SOURCE
GIS DATA INPUTS		
Rainfall Erosivity (R)	Index variable of erosion potential as a function of rainfall intensity and duration	Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C, coordinators. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). United States Department of Agriculture, Agriculture Handbook No. 703. 1997.*
Soil Erodibility (K)	Susceptibility of soil particles to detachment and transport	SUURGO*
OTHER DATA INPUTS		
C Factor	Crop/vegetation management factor	Literature review (Exhibit 28)
Sediment Retention Efficiencies	Capacity of LULC type to retain sediment as a function of vegetation type (percent)	Literature review (Exhibit 29)
* Site-specific data for Delaware.		

EXHIBIT 28. CROP AND VEGETATION MANAGEMENT FACTOR INPUTS TO THE USLE BY LULC TYPE

LULC TYPE	ASSUMPTION/SOURCE	C COEFFICIENT
Built	Average of estimates for development of varying densities from two studies: • Georgia Environmental Protection Division. Total Maximum Daily Load Evaluation for Eight Stream Segments in the Tennessee River Basin for Sediment. Submitted to the USEPA. January 2004. (Georgia EPD, 2004) • Indiana Department of Environmental Management. Limberlost Creek Watershed Sediment and Nutrient TMDL Assessment. Appendix A. Prepared for the USEPA. 2007. (Indiana DEM, 2007)	.017
Agriculture	Average of multiple estimates for various row crops from three studies: • Georgia EPD, 2004 • Indiana DEM, 2007 • Ohio Environmental Protection Agency, Division of Surface Water. Total Maximum Daily Loads for the Salt Creek Watershed. Appendix C. 2009. (Ohio EPA, 2009)	.278
Rangeland	Average of estimates for grasslands and herbaceous lands from four studies: • Georgia EPD, 2004 • Indiana DEM, 2007 • Ohio EPA, 2009 • Montana Department of Environmental Quality. Upper Jefferson River Tributary Sediment TMDLs and Framework Water Quality Improvement Plan. Appendix D. September 2009. (Montana DEQ, 2009)	.012
Forest	Average of deciduous and evergreen forest types from three studies: • Indiana DEM, 2007 • Ohio EPA, 2009 • Montana DEQ, 2009	.002
Water	Georgia, 2004	0
Bare Soil/Sand	Georgia, 2004	0
Non-Forested Wetlands	Average for emergent and herbaceous wetlands from two studies: • Indiana DEM, 2007 • Georgia, 2004	.002
Forested Wetlands	Average of woody wetlands from three studies: • Indiana DEM, 2007 • Ohio EPA, 2009 • Georgia, 2004	.006
Note: While C Factors may vary across landowners, the sources for these estimates are studies for which general C factors were calculated for various for land use types.		

EXHIBIT 29. SEDIMENT RETENTION EFFICIENCIES BY LULC TYPE

LULC TYPE	ASSUMPTION/SOURCE	SEDIMENT RETENTION EFFICIENCY
Built	Non-vegetated land use unlikely to filter sediment	0%
Agriculture	Average value for multiple crops (including sorghum, cane, corn, and oats) from three studies: • Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. "Filter Strip Performance and Processes for Different Vegetation, Widths, and Contaminants." *Journal of Environmental Quality* 28 (1999): 1479-1489. • Schoonover, Jon E., Karl W. J. Williard, James J. Zaczekjean C. Mangun, and Andrew D. Carver. "Agricultural Sediment Reductions by Giant Cane and Forest Riparian Buffers." *Water, Air and Soil Pollution* 169 (2006): 303-315. • Young, R.A., T. Huntrods, and W. Anderson. "Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff." *Journal of Environmental Quality* 9 (1980): 483-487.	87%
Rangeland	Value from two studies: • Hook, P.B. "Wetlands and Aquatic Processes: Sediment Retention in Rangeland Riparian Buffer" *Journal of Environmental Quality* 32 (2003): 1130-1137. • Van Dikj, P.M., F.J.P.M. Kwaad, M. Klapwijk. "Retention of Water and Sediment by Grass Strips." Hydrological Processes 10 (1996): 1069-1080.	99%
Forest	Based on study at the Rhode River, Chesapeake Bay: • Correll, D.L., T.E. Jordan, D.E. Weller. "Nutrient Flux in a Landscape: Effects of Coastal Land Use and Terrestrial Community Mosaic on Nutrient Transport to Coastal Waters." Estuaries. 15 (1992): 431-442.	94%
Water	Non-vegetated land use unlikely to filter sediment	0%
Bare Soil/Sand	Average of three estimates from: • Abu-Zreig, M., Rudra, R.P., Lalonde, M.N., Whiteley, H.R., Kaushik, N.K. "Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. Hydrological Processes." 18 (2004): 2029-2037.	25%
Non-Forested Wetlands	Value estimate from: • Chesapeake Bay Program Scientific and Technical Advisory Committee (STAC).Quantifying the Role of Wetlands in Achieving Nutrient and Sediment Reductions in Chesapeake Bay. November 2008.	69%
Forested Wetlands	Based on estimate for forests.	94%
Notes: Where available, we applied the data from studies with the LULC types closest to Delaware and that were based on geographic locations closest to Delaware.		

Exhibit 30 provides the results of this analysis in terms of increased sediment loading to waterways due to the wetland losses in our future scenario. Overall, the increase is relatively modest, and comparable to the change in nutrient loading. Again, the greatest increase in loading is in the Delaware Bay drainage, which is subject to the greatest level of wetland loss in our future scenario.

EXHIBIT 30. CHANGE IN NUTRIENT RETENTION AS A RESULT OF WETLAND LOSSES: 2007-2022

DRAINAGE	WETLAND ACRES LOST	PERCENT CHANGE IN SEDIMENT LOADING
Piedmont	381	0.9%
Delaware Bay	1,615	2.5%
Chesapeake Bay	734	0.7%
Inland Bays	402	0.9%
STATEWIDE	**3,132**	**1.3%**

3.3 ECONOMIC VALUE

The output of the nutrient and sediment retention models is linked to an economic valuation model in order express the biophysical change in these water quality parameters in monetary terms. We value the degraded water quality resulting from the wetland losses in terms of increased treatment costs. In other words, the value of the wetlands in purifying water is expressed as the equivalent cost of replacing this service with additional municipal water treatment.

We apply recent cost estimates for nitrogen removal calculated by DNREC of $85 per pound (~$188/kg in 2010 dollars). This represents the cost of removing nitrogen by connecting an onsite wastewater treatment and disposal system to sewer districts.[29] Thus, we assume the increased nitrogen exported to waterways in our future scenario is removed in this manner at a cost of $85 per pound. In some cases, other wastewater treatment methods may be employed, such as a developing a wastewater treatment plant or an advanced on-site treatment system. In these cases the costs of the additional nitrogen removal could be greater.

As nitrogen is removed, some amount of phosphorus is simultaneously filtered. Conversations with a water quality expert at DNREC indicate that, generally, each pound of nitrogen removed results in the removal of approximately one-third a pound of phosphorus.[30] Based on our forecast of increased nutrient loading, all of the phosphorus would be removed by way of treating the water for nitrogen. This outcome is consistent with the experience of DNREC water quality experts. Thus, the $85 per pound applied to all of our added nitrogen loadings will also remove all of the added phosphorus.

In addition, applying a damage function approach, a recent USDA Economic Research Service Report estimates that the soil conservation benefits associated with sediment removal are relatively low on a per ton basis. Specifically, the benefit of removing sediment (or cost of not removing sediment) is estimate at $0.06 to $1.45 per ton.[31] This is consistent with the economics literature

[29] Delaware Department of Natural Resources and Environmental Control, Division of Water Resources. Inland Bays Pollution Control Strategy. May 2008. The costs in the DNREC report were Inflated to 2009 dollars using the GDP deflator to ensure all values in this report are in like dollar years.

[30] Per communication with Lyle Jones, DNREC, on January 5, 2011.

[31] Hansen, LeRoy and Marc Ribaudo. Economic Measures of Soil Conservation Benefits: Regional Values for Policy Assessment. U.S. Department of Agriculture, Economic Research Service Technical Bulletin 1922. September 2008. Benefits estimates from the study are inflated to 2010 dollars for comparison with the cost estimates in this report.

regarding the relatively low municipal treatment costs of removing sediment. A frequently-cited 1988 Land Economics study estimated that sediment discharges to surface water increase treatment costs by $18 to $46 per thousand tons of sediment discharged.[32] Based on our estimates of added sediment loading due to wetland loss, the total added cost of sediment treatment is dominated by the costs of additional nitrogen treatment. Overall, the results of our analysis, presented in Exhibit 31, are therefore primarily a function of the estimated increase in nitrogen loading associated with wetland decline.

To estimate the present value of increased water treatment costs over time, we assumed linear increases in the pollutant levels between 2007 and 2022, with the full statewide increase in pollutant loading occurring by 2022. We then multiply the increased annual loading by per unit treatment costs ($85 per pound of nitrogen) and apply a three percent social discount rate to quantify the present value of these losses.[33] Exhibit 31 provides the total present value costs of treating excess pollutants in the Delaware waterways due to a forecast 1.2 percent decline in wetlands by 2022.

EXHIBIT 31. ECONOMIC VALUE OF DECREASED WATER PURIFICATION CAPACITY DUE TO WETLAND LOSSES: 2007-2022

DRAINAGE	WETLAND ACRES LOST	COST OF TREATING INCREASED POLLUTANT LOADING: 2007-2022 (PV, 3% DISCOUNT RATE)
Piedmont	381	$1,140,000
Delaware Bay	1,615	$4,310,000
Chesapeake Bay	734	$2,830,000
Inland Bays	402	$1,380,000
Statewide	**3,132**	**$9,670,000**
Notes: Value estimates are rounded to three significant digits and may not sum due to rounding error. All cost estimates presented are expressed in 2010 dollars.		

3.4 KEY UNCERTAINTIES

Exhibit 32 summarizes the key uncertainties associated with the water purification analysis. These uncertainties are ranked in terms of their significance with respect to the results of this analysis. As described in Section 3.1, while this analysis involves multiple variables and data sources, much of the data applied are specific to Delaware (both biophysical and economic data). Thus, we anticipate the results of the water purification analysis are subject to less uncertainty overall, than the carbon storage analysis.

[32] Holmes, Thomas P. "The Offsite Impact of Soil Erosion on the Water Treatment Industry." Land Economics 64 (4) (1988). Benefits estimates from the study are inflated to 2010 dollars for comparison with the cost estimates in this report.

[33] For each service-specific analysis, we present economic impacts incurred over time in present value terms. The present value represents the value of a cost or benefit or stream of costs or benefits in common dollar terms. That is, it is the sum of a series of past or future cash flows expressed in today's dollars. We apply a three percent discount rate to calculate the present value impacts, a common social discount rate applied by economists.

EXHIBIT 32. KEY UNCERTAINTIES ASSOCIATED WITH THE WATER PURIFICATION ANALYSIS

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES
No accounting for chemical or biological interactions besides filtration by ecosystem vegetation and soils	**Unknown.** May overestimate or underestimate treatment costs	**Probably minor.** The model specifically accounts for the capacity of the landscape to filter the pollutants. In fact, other interactions may also diminish the level of pollutant as it flows across the landscape (e.g., interactions with the air, water and other pollutants). To the extent that the pollutant levels are dissipated by other factors before reaching the waterways, this analysis overestimates the level of pollutant loading. However, this overestimation would occur both in our baseline and future scenarios and thus the effect on the difference between the scenarios (which is what we value in this analysis) is likely minor.
Where specific data were not available regarding nutrient and sediment filtering efficiencies, we applied proxies of the most closely matched study in terms of land use type and geographic location	**Unknown.** May overestimate or underestimate treatment costs	**Probably minor.** While the nutrient and sediment filtering efficiency data were limited for some land use types, the estimates we applied were reviewed by the lead hydrologist for the InVEST project, and we anticipate they are reasonable approximations applying the best available data and expert opinion.
Nutrient loading rates are averages for each LULC type for each drainage	**Unknown.** May overestimate or underestimate treatment costs	**Probably minor.** While data were not available on nutrient loading rates for every watershed across the landscape, we applied averages from available field studies data for watersheds in each drainage. While some parcels may vary above or below this average, we anticipate applying the average results in a relatively low error level.
C Factors (crop management factors) are not specific to Delaware lands but were transferred from available studies	**Unknown.** May overestimate or underestimate treatment costs	**Negligible.** Because the costs of sediment treatment are so low compared to nitrogen treatment, the additional sediment loading had a negligible effect on the total present value treatment cost in our analysis. Thus, refinements to the crop management factors are not expected to measurably alter our results.
Absent specific information on soil conservation practices (P Factors), we did not include this variable in the USLE calculations	May **overestimate** treatment costs	**Negligible.** Controlling for soil conservation efforts may reduce our estimate of the amount of additional sediment loading to waterways. The costs of nitrogen removal, however, already overwhelm the costs of sediment removal and, thus, incorporating this factor is not likely to change our results.

SECTION 4 | FLOOD PROTECTION

Photo from DNREC website

A key service provided by wetland ecosystems stems from their ability to act as a sponge, absorbing excess water and mitigating flooding from storm events. Wetlands can hold this excess water and then return it to surface and groundwater over time as water levels abate.[34] Wetlands adjacent to rivers and streams intercept runoff, buffering inland properties from increased river heights due to periods of high rainfall. Likewise, coastal wetlands protect coastal regions by attenuating storm surges. A 1985 study of the Chesapeake Bay drainage basin concluded that, where wetlands covered four percent of a basin, flood flow was half that of basins that did not contain any wetlands.[35] This wetland service is of particular economic value because flood events have been known to generate significant economic impacts, including damages to residential and commercial development and transportation infrastructure. Furthermore, the frequency and intensity of flood events is increasing nationally. The number of flood events was six times greater in the 1990s than the 1960s, and average annual property damages increased by nine times over the same time period.[36]

This chapter describes the methods and results of two models applied to demonstrate the value of Delaware wetlands in mitigating flood impacts. We first present the InVEST storm peak model, applied to evaluate how the presence of wetlands affects flood area and height associated with a 25-year, 24-hour rainfall event at four case study sites. Section 4.2 describes the coastal storm surge model applied to estimate the contribution of coastal wetlands in attenuating storm surge. We quantify the economic costs of wetland loss in terms of increased property damages due to inland and coastal flood events in Section 4.3. Section 4.4 describes the key uncertainties associated with this analysis.

---

[34] Mitsch, William J. and James G. Gosselink. Wetlands. Fourth Edition. Hoboken, NJ: John Wiley and Sons, Inc., 2007.

[35] *Ibid.*

[36] Brody, Samuel D., Sammy Zaheran, Praveen Maghelal, Himanshu Grover, and Wesley E. Highfield. "The Rising Costs of Floods." Journal of the American Planning Association 73(3) (2007): 330-345.

4.1 STORM PEAK MODEL DESCRIPTION[37] AND BIOPHYSICAL CHANGE

We apply the InVEST storm peak mitigation model to quantify how the presence of wetlands affects the probability of stormwater reaching inland properties. The model estimates the relative contribution of particular areas (pixels within the watershed maps) to flood potential following a storm. Importantly, the model considers only one type of potential flooding by focusing on properties within floodplains of streams and rivers. In fact, additional flooding potential may be associated with, for example, “ponding” of stormwater in inland areas.

The GIS model generates a hydrograph for a select watershed applying information on the characteristics of each 30 by 30 meter pixel to estimate the time it takes for stormwater runoff from each pixel to reach the watershed outlet. Specifically, the model incorporates information on level of rainfall (i.e., “storm depth”), as well as land use specific soil and vegetation characteristics, surface roughness (affecting the velocity of the runoff) and slope. We also incorporate assumptions regarding the capacity of wetlands to store the runoff as it travels across the landscape (i.e., “wetland depth”). In other words, as water falls on the landscape, runoff travels downslope to the watershed outlet. The amount and timing of water reaching the outlet is a function of the capacity of each pixel to slow or store the water. For example, more densely vegetated land use pixels, such as forests, are better at slowing runoff than bare lands and impervious surface.

In order to estimate the contribution of wetlands in mitigating flood extent and level, we first run the model according to our 2007 baseline scenario. We then re-ran the model for our 2022 wetland loss scenario. The difference in flood height and extent between the two scenarios represents the change in flood characteristics due to the forecast continued wetland loss over the next 15 years.

Due to the geographic specificity of the model, we were not able to model flooding from a particular storm event across the entire State of Delaware. Consistent with other existing flood models, the InVEST storm peak model performs best at the watershed level. We therefore simulated the flooding resulting from a 25-year, 24-hour rainfall event at four subwatersheds across the state (one in each of the main drainages). The results at these four sites provide insight into the implications of wetland loss on flood damages in Delaware. It is important to note also, that this analysis only models one type of storm event (a 25 year rainfall event) and not all types of storms that may result in flooding in the state.

4.1.1 DESCRIPTION OF MODEL METHODS

The following stepwise description of the model specifies the functions applied to estimate flood area and height for each of the scenarios.

[37] The InVEST storm peak model was under development by the Natural Capital Project as of the writing of this report, and has therefore not been included in the publically available InVEST tool and user’s guide. Testing and application of the model for this analysis were facilitated by Dr. Driss Enaanay, Lead Hydrologist at the Natural Capital Project (Stanford University) and Dr. Kent Kovacs, Economist with the Natural Capital Project (University of Minnesota). The documentation of the model was provided to IEc in the following: Dr. Driss Ennaanay. March 2011. Memorandum to Industrial Economics, Inc. “Tier 1 Storm Peak Mitigation Model.”

Step 1: identify Points of Interest for which the Model Will Estimate Flood Area and Depth

The storm peak model estimates flooded area and flood height around a specified "point of interest." In our case, the point of interest is the outlet point of the watershed. Thus, all pixels upslope of the outlet may contribute runoff that eventually pools upslope of the outlet point. For this analysis, we estimated the flooded area along a stream by specifying multiple points of interest at two kilometer intervals along the stream in order to simulate the flooded area along the entire stream reach. This allows us to account more fully for flooding along the stream and not limit the analysis to the area directly upslope of the outlet point. In effect, we delineated subwatersheds along the stream in order to model a flood event. We undertake the following specific steps for each subwatershed along each stream evaluated.

Step 2: Calculate the Velocity of Runoff as it Travels across the Landscape

The InVEST model estimates the time it takes for rainfall on each pixel "x" within a landscape to reach the drainage point "D" as a function of land use downslope of the pixel. These drainage points are the outlet points for each of the subwatersheds delineated in Step 1. First the model estimates the velocity of runoff as it crosses each pixel, as follows:

$$v_x = (1/c_r) * \sqrt{\theta_x}$$

Where:

v_x = The overland flow velocity of pixel x.

c_r = The "roughness coefficient" of each pixel as determined by land use type (see Exhibit 35).

θ_x = The mean percent slope of pixel x.

The roughness coefficient in this equation relates slope and surface vegetation to velocities. Mean percent slope is estimated using a digital elevation model (DEM) of the watershed.

Step 3: Estimate Travel Time for Excess Rainfall to Reach the Watershed Outlet Point

The total travel time for runoff to reach the drainage point is a function of velocity of water on each pixel and the distance it travels across each pixel, as follows:

$$T_{xD} = \sum_{x}^{x_n} (y_x/v_x)$$

Where:

T_{xD} = Time for storm runoff from pixel x to reach drainage point D.

y_x = The distance runoff flows across pixel x.

θ_x = The mean percent slope of pixel x.

The distance runoff travels across a pixel (y_x) is a function of the pixel size (in this case, the watershed is divided into 30 by 30 meter pixels). For example, if water is flowing directly from north to south, y_x = 30. Where water flows southeast, the distance travelled is equal to the hypotenuse of the pixel. The total travel time is a sum of the travel times for the runoff to travel across all pixels (from x to Xn) between x (pixel on which the rainfall is deposited) and drainage point D.

Step 4: Calculate the Direct Runoff Generated by Each Pixel

The InVEST model applies the well-established "SCS-Curve Number" equations to calculate direct runoff from each pixel. This is a method developed by the U.S. Department of Agriculture's Soil Conservation Service (SCS) and frequently applied by hydrologists to approximate runoff from a rainfall event.[38] The method considers the temporal dynamics of a storm event and storm runoff generated. Direct runoff is generated by both surface and subsurface flow processes. Hortonian overland flow occurs when rainfall exceeds infiltration capacity; saturation overland flow occurs after the soil profile becomes saturated; and shallow subsurface flow occurs when water flows downslope into shallow soil profiles. The curve number method computes the runoff from the land surface and quantifies runoff from areas with soil surface saturation.

The model assumes that the rain falls at a constant rate during the storm event and falls uniformly across the watershed. The following equations determine the direct runoff at pixel x per the SCS-Curve Number method as follows:

$$S_x = (25400/CN_x) - 254$$

$$\text{If } P_s < 0.2S_x \rightarrow Q_{sx} = 0$$

$$\text{If } P_s > 0.2S_x \rightarrow Q_{sx} = (P_s - 0.2S_x)^2/(P_s + 0.8S_x)$$

Where:

S_x = Potential maximum soil retention at pixel x.

CN_x = Curve Number associated with the particular land use on pixel x (see Exhibit 34). These estimates are empirically derived by the SCS.

P_s = Rainfall depth of a given storm event (see Exhibit 33).

Q_{sx} = Direct runoff generated by the storm event at pixel x.

The P_s value of $0.2S_x$ is the initial abstraction accounting for the amount of precipitation that falls before runoff occurs due, for example, to infiltration or interception by vegetation. The standard assumption for this value was set by the SCS based on historical study.

[38] U.S. Dept. of Agriculture. Soil Conservation Service. 1972. National engineering handbook, Section 4, hydrology. Chapters 7, 8, 9, and 10. U.S. Govt. Print. Off. Washington, DC.

Generally, the SCS recommends the above method to estimate runoff for slopes of less than five percent. The InVEST model therefore employs an adjustment to the CN value recommended in the hydrological literature for slopes different than five percent, as follows:[39]

$$CN_{x,adj} = ((100-CN_x)/3) * (1 - 2* \exp(-13.86*\theta_x)) + CN_x$$

Where:

$CN_{x,adj}$ = Adjusted Curve Number associated with the particular land use on pixel x.

θ_x = Mean percent slope of pixel x.

Step 5: Incorporate Storage Capacity of Wetlands

The InVEST model accounts for the capacity of wetlands to store runoff from upslope pixels as the water flows to the drainage point. This is accomplished by developing a GIS map of wetlands and assigning a storage value to the wetlands (see Exhibit 33). The water entering the wetland pixels from upslope are filled with water to the maximum depth, beyond which all water flowing into the wetland then flows directly out.

Step 6: Estimate Volume of Water Reaching Streams

The model combines the calculated information on volume and timing of runoff, accounting for wetland storage, as described above, to quantify the timing and water volume that reaches ditches and streams and is then delivered to the outlet of the watershed. This combination of the time classes (classes of pixels with similar travel times between pixel and outlet) and water volumes generates the hydrograph. The highest storm volume generated by the hydrograph is the storm peak, at which the water heights are greatest. These are the water heights reported in our results.

Step 7: Delineate Flood Area and Calculate Flood Depth

As described above, a landscape is limited in its ability to absorb water, for example, by vegetation type and extent, soil profile, and wetland water storage capacity. The volume of runoff within the watershed at the time of storm peak pools around the streams and outlet points downslope.[40] The InVEST model maps the area flooded due to the storm peak water volume and provides values of the water height at those points. To calculate flood depth from water height provided by InVEST, we subtracted the elevation of the land (provided by the DEM) from the water height. The DEM applied in this case provides elevation at a 10 by 10 meter grid cell level. Thus, our analysis calculates flood depths within the watershed at this resolution.

[39] Calculation for adjustment developed by Williams (1995) as reported in: Saleh, D.K., Kratzer, C.R., Green, C.H., and Evans, D.G., 2009, Using the Soil and Water Assessment Tool (SWAT) to simulate runoff in Mustang Creek Basin, California: U.S. Geological Survey Scientific Investigations Report 2009-5031.

[40] Stormwater may also pool inland, for example, on farmland or former wetland areas. This analysis, however, only models one type of flooding associated with storm events and does not estimate the effect of our wetland loss scenario on other types of flooding.

4.1.2 DESCRIPTION OF DATA INPUTS FOR THE STORM PEAK MODEL

Exhibit 33 describes the sources for the various model inputs described above. The map inputs include a ten by ten meter DEM for the state. To this, we incorporated information on ditches in order to account for the effect of these features on runoff patterns following a storm event. The wetland maps act as a "mask" in the model, assigning water retention values to the wetlands such that they act as a reservoir to retain the rainfall and runoff. Because wetland depth is quite variable across the state, we run the models assuming low and high end ranges of wetland depth of zero and one meter, respectively. We chose to model flooding in the state following a 25-year, 24-hour storm event, as described below. We assume the frequency of these events is once every 25 years.

EXHIBIT 33. DATA REQUIREMENTS FOR INVEST STORM PEAK MODEL

DATA INPUT	PURPOSE IN MODEL	DATA SOURCE
GIS DATA INPUTS		
LULC map of Delaware	Describes land use and land cover characteristics	Sanborn Map Company, Inc. 2007 Delaware Land Use and Land Cover [ESRI Shapefile]. 1st Edition. State of Delaware, Office of Management and Budget, Delaware Geographic Data Committee. 2007.
Digital Elevation Model (DEM)	Used to model water flow across landscape; the ten by ten meter USGS DEM is modified to incorporate ditches across the State of Delaware	U.S. Geological Survey (USGS) National Elevation Data, Delaware 1-Arc Second, Series Issue 0.1. Sioux Falls, SD: U.S. Geological Survey, 2002 – 2005.* Institute for Public Administration, Water Resources Agency College of Human Services, Education and Public Policy, University of Delaware. 2008. Development of Hydrogeomorphic Modifiers to the Statewide Wetlands Mapping Project (SWMP) Dataset for Selected Watersheds in the Delaware Estuary, State of Delaware. Summary report for Department of Natural Resources and Environmental Control. 34pp.* Tiner, R.W., H.C. Bergquist, J.Q. Swords, and B.J. McClain. 2001. Watershed-based Wetland Characterization for Delaware's Nanticoke River Watershed: A Preliminary Assessment Report. U.S. Fish & Wildlife Service, National Wetlands Inventory (NWI) Program, Northeast Region, Hadley, MA. Prepared for the Delaware Department of Natural Resources and Environmental Control, Division of Soil and Water Conservation, Dover, DE. NWI technical report. 89 pp. plus 22 maps.*
Enhanced National Wetland Inventory (NWI) maps for the State of Delaware	Describes the most recent information on the distribution of wetlands in Delaware	McGuckin, K. 2011. Methods Used to Create Datasets for the Delaware State Wetlands Update. Conservation Management Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA.
OTHER DATA INPUTS		
Wetland Depth	Water storage in wetland (m)	Wetland depth is variable across the state. For modeling purposes ran the model applying two wetland depth assumptions: 0 and 1 meter.

DATA INPUT	PURPOSE IN MODEL	DATA SOURCE
Storm Depth	Rainfall associated with a 25 year, 24 hour storm depth. Estimate is 161.54 mm (6.36 inches)	U.S. EPA. November 2009. Development Document for Final Effluent Guidelines and Standards for the Construction and Development Category. Table 3-3, "Rainfall Summary Data for Indicatory Cities."
Runoff Curve Number	Predicts runoff from rainfall; land use specific	Multiple (see Exhibit 34)
Roughness	Roughness coefficient is a land use specific constant used to define the velocity of runoff across the land	Multiple (see Exhibit 35)
* Site-specific data for Delaware.		

As described above, the roughness ("c") and curve number ("CN") are factors in determining the timing and volume of runoff from a given pixel of a particular land use type. The runoff curve number can be thought of as runoff potential for a pixel of a particular land use. It is used to predict direct runoff or infiltration from rainfall excess. The curve number is a function of multiple site-specific factors, including hydrologic soil group, hydrologic condition, and vegetation type. We assumed hydrologic soil type B for Delaware based on a Soil Conservation Service 1986 technical release, as cited in Exhibit 34. Using this information, we assign general curve numbers by land use type in the state from SCS publications, as described in Exhibit 34. Values for CN range from 30 to 100; lower numbers indicate low runoff potential while larger numbers indicate greater runoff potential. Because they are a function of multiple site-specific characteristics (e.g., vegetation type and density, soil condition), curve numbers may vary greatly across a landscape, even within a given land use type. While it would be preferable to apply specific, measured curve numbers for each pixel, these data are not available. We therefore rely on the best available information on average curve numbers by general land use type. For the modeling exercise, the relative curve numbers by land use type are important. Wetland and forest ecosystems are associated with relatively low levels of stormwater runoff (i.e., their soils and vegetation can absorb more of the storm water), whereas built lands and water (i.e., lakes and ponds) are associated with relatively high levels of runoff that contribute to flooding.

EXHIBIT 34. LAND USE SPECIFIC CURVE NUMBER VALUES

LULC TYPE	RUNOFF CURVE NUMBER	SOURCE
Built	98	Soil Conservation Service, 1986. Urban Hydrology for Small Watersheds. Technical Release 55, Washington, D.C. (SCS, 1986)
Agriculture	81	Chow, V.T., D.R. Maidment, and L.W. Mays, 1988, Applied Hydrology,. McGraw-Hill Book Company.
Rangeland	61	SCS, 1986
Forest	55	SCS, 1986
Water	100	SCS, 1986

LULC TYPE	RUNOFF CURVE NUMBER	SOURCE
Bare Soil/Sand	82	SCS, 1986
Estuarine Vegetated Wetlands	58	SCS, 1986
Estuarine Non-Vegetated Wetlands	82	SCS, 1986
Palustrine Aquatic Bed Wetlands	100	SCS, 1986
Palustrine Emergent Wetlands	58	SCS, 1986
Palustrine Forested Wetlands	55	SCS, 1986
Palustrine Scrub Shrub Wetlands	61	SCS, 1986
Note: Absent site-specific information on curve numbers across the Delaware landscape, values were selected for various land use types according to expert advice from Dr. Driss Enaanay, Lead Hydrologist, Natural Capital Project, Stanford University.		

The hydraulic roughness of a land use type is the measure of the amount of frictional resistance water experiences when passing over land and channel features. An increase in this value will cause a decrease in the velocity of water flowing across a surface, as described above. Exhibit 35 describes the values and sources for the roughness coefficients applied in this analysis.

EXHIBIT 35. LAND USE SPECIFIC ROUGHNESS COEFFICIENTS

LULC TYPE	ROUGHNESS COEFFICIENTS	SOURCE
Built	15	Montes, S. Hydraulics of Open Channel Flow. Baltimore: American Society of Civil Engineers, 1998. (Montes, 1998)
Agriculture	40	Montes, 1998
Rangeland	70	Montes, 1998
Forest	200	Montes, 1998
Water	80	Brater, E.F., and King, H.W. Handbook of Hydraulics for the Solution of Hydraulic Engineering Problems. New York: McGraw-Hill, 1976. (Brater and King, 1976)
Bare Soil/Sand	55	Brater and King, 1976
Estuarine Vegetated Wetlands	125	Brater and King, 1976
Estuarine Non-Vegetated Wetlands	125	Brater and King, 1976
Palustrine Aquatic Bed Wetlands	125	Brater and King, 1976
Palustrine Emergent Wetlands	125	Brater and King, 1976
Palustrine Forested Wetlands	200	Montes, 1998
Palustrine Scrub Shrub Wetlands	125	Brater and King, 1976
Note: Values are the coefficients multiplied by 1000 for application in the model. That is, the coefficient for built is actually 0.015.		

4.1.3 RESULTS OF FLOODED AREA AND DEPTH: FOUR CASE STUDY SITES

As noted previously, the storm peak model works best at a watershed level. In consultation with experts at DNREC, we therefore selected four case study sites across the state to model changes in flood height and extent following a 25-year, 24-hour rainfall event. The following streams were selected as case study sites:

- Red Clay Creek in the Piedmont Drainage;
- Blackbird Creek in Delaware Bay Drainage;
- Clear Brook in Chesapeake Bay Drainage; and
- Cow Bridge Branch in Inland Bays Drainage.

These sites were identified because each site experiences some level of wetland loss associated with our 2022 wetland loss scenario, as indicated in Exhibit 36, but otherwise vary in terms of surrounding land uses and other characteristics. Because of the variability in results depending on site-specific factors, such as extent of wetland loss, existing land use and land cover, and regional topographical and hydrological factors, we do not suggest scaling the results of this analysis to estimate a statewide cost of flood damage due to wetland loss. Instead, the case study approach underscores the importance of wetlands in attenuating flooding while highlighting the variability in stream flooding across the state.

As described in Step 1, we divided each of these sites into subwatersheds in order to estimate changes in water levels. Exhibit 36 describes the results of the storm peak model for each subwatershed at each case study site. Importantly, the water heights presented in Exhibit 36 are **not flood heights of the water above the land**. The output of the InVEST model is the height of the water above sea level. In order to estimate flood height, we need to subtract the elevation of the land (as described in Step 7. Once the DEM is subtracted, however, there is variation in flood height at the 10 by 10 meter grid cell level and, thus, does not lend itself to presentation in a table. Appendix A provides the flood heights (in meters) in each affected structure. Exhibit 36 is helpful, however, in describing how wetland losses are affecting water height, and under which scenarios there is the potential for incremental flood damages due to wetland loss (i.e., where there occurs a change in water height between 2007 and 2022). Exhibit 36 also indicates where the flooded area overlaps land parcels zoned for residential development. Subwatersheds that include residential development for which flood height increases between 2007 and 2022 may experience flood damage to homes as described in Section 4.3. Exhibit 36 also presents the estimated acreage of wetland losses that generate the incremental flooding and damages reported in this analysis.

For the most part, we expect minor, if any, changes in the extent of flooding. An exception is Blackbird Creek, for which we identified some increase in the extent of area flooded. The differences in flooded area, where applicable, are observable in Exhibits 37 through 40. The primary effects of the wetland losses, however, are increases in the height of floods (as opposed to area flooded).

Exhibit 36 indicates very minor changes in flood heights between 2007 and 2022 associated with our zero meter wetland depth assumption. Under this assumption, wetlands do not act as reservoirs to collect water. The wetlands are, however, still relatively effective at storing and slowing runoff in the model due to their relative curve numbers and roughness coefficients. In some cases, minor decreases in water height are forecast under the zero meter wetland depth assumption. This error is a result of the resolution of the model data, a ten by ten meter resolution. More refined spatial data on elevation and stream width would decrease this error.

According to our one meter wetland depth assumption, measurable changes in water height are identified in subwatersheds along both Red Clay Creek and Blackbird Creek, and to a lesser extent Clear Brook. These increases in flood height are generally on the order of inches. As described in Exhibit 36, however, one subwatershed of Blackbird Creek is forecast to experience flood height increases of up to almost 1.5 meters (59 inches) due to the projected wetland losses. This relatively great change in flood heights is likely due to the relatively great level of projected wetland losses within the Blackbird Creek watershed. As described in Exhibit 36 and mapped in Exhibits 37 through 40, our analysis forecasts wetland losses in Blackbird Creek of approximately 138 acres. This is compared to approximately 53 acres in Red Clay Creek, 68 acres in Cow Bridge Branch, and 14 acres of projected wetland losses in Clear Brook. This greater extent of projected wetland loss (more than twice the area of wetland loss of any of the other watersheds) means that, under the one meter wetland depth assumption, the Blackbird Creek watershed likely lost more than twice the stormwater storage capacity due to wetland losses than the other watersheds.

Our model did not forecast changes in water height at Cow Bridge Branch for this type of storm event. The bolded entries in Exhibit 36 indicate watersheds and scenarios under which the wetland losses result in increased water heights. The blue shaded entries indicate subwatersheds for which the incremental flooding may affect existing residential development.

Exhibits 37 through 40 highlight the flooded area at each of these sites. These exhibits demonstrate where the flooded area overlaps development and other land use activities. Where the flooded area overlaps productive land use, and the flood heights are incrementally increased due to wetland loss, we consider the potential for incremental economic damages. Section 4.3 describes our approach to valuing potential incremental damages of increased flooding due to the wetland losses.

EXHIBIT 36. FLOOD HEIGHT CHANGES DUE TO WETLAND LOSS

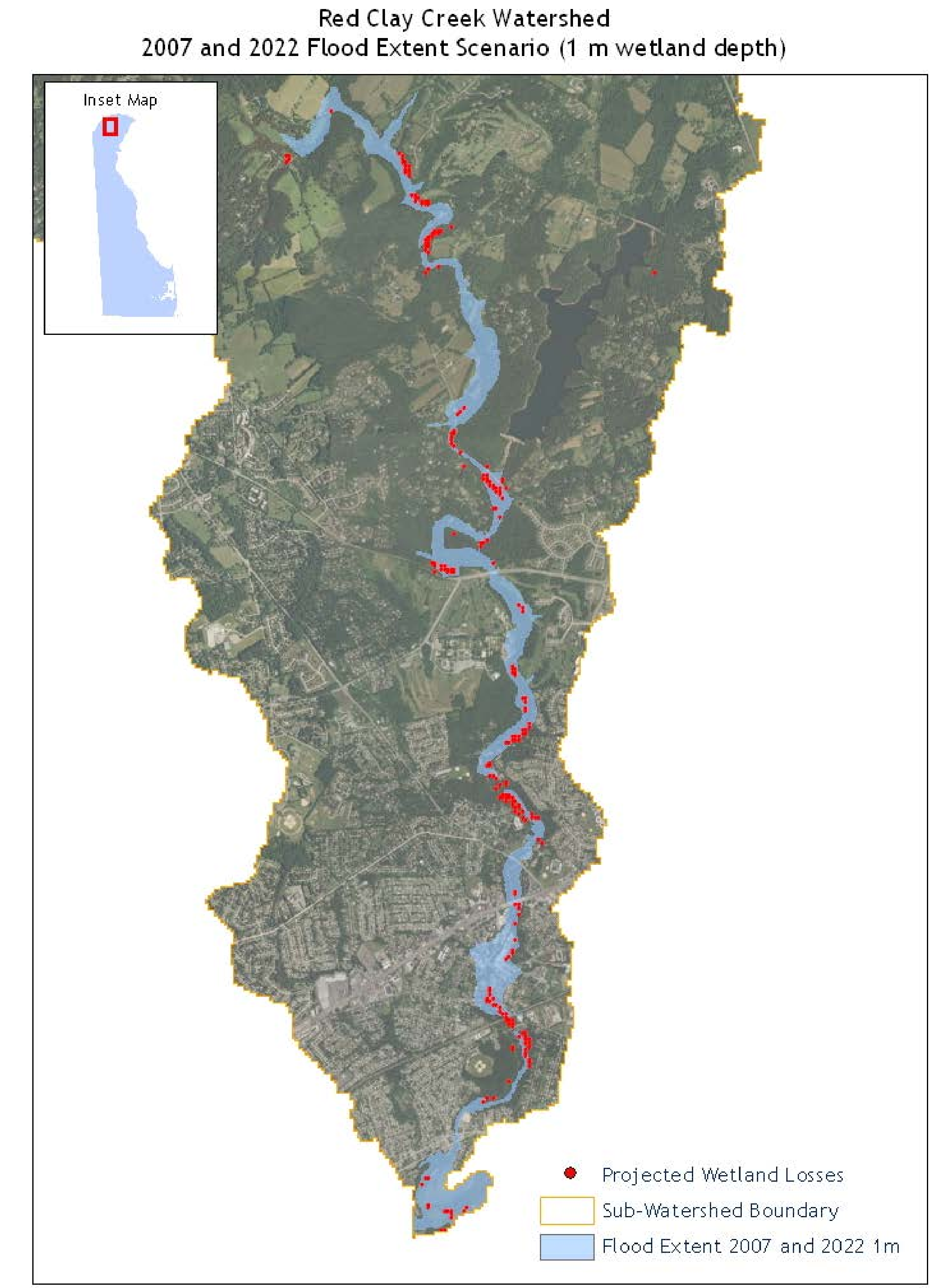
WATERSHED (PROJECTED WETLAND LOSS)	SUB	OUTLET POINT HEIGHT (M)	1M WETLAND DEPTH		0M WETLAND DEPTH		OVERLAP WITH DEVELOPMENT?
			2007 FLOOD HEIGHT (M)	2022 FLOOD HEIGHT (M)	2007 FLOOD HEIGHT (M)	2022 FLOOD HEIGHT (M)	
Red Clay Creek **(53 acres)**	1	49.61	0.00	0.00	0.00	0.00	no
	2	41.069	43.00	43.00	43.00	43.00	yes
	3	35.811	41.00	41.00	41.00	41.00	no
	4	32.695	36.87	36.87	37.33	37.33	yes
	5	24.83	**32.099**	**32.11**	32.61	32.61	yes
	6	15.512	**27.83**	**27.86**	28.37	28.36[a]	yes
	7	5.555	**17.82**	**17.84**	18.459	18.459	yes
	8	4.87	5.41	5.41	5.54	5.54	yes
Blackbird Creek **(138 acres)**	1	10.925	0.00	0.00	0.00	0.00	no
	2	5.13	**7.43**	**8.90**	**8.89**	**8.91**	no
	3	1.726	**4.3**	**5.27**	**5.27**	**5.28**	no
	4	0.98	**1.68**	**2.09**	2.11	2.10[a]	no
	5	0	**0.58**	**0.80**	0.80	0.80	yes[b]
	6	0	**0.12**	**0.22**	0.22	0.22	no
	7	0	0.00	0.00	0.00	0.00	no
Clear Brook **(14 acres)**	1	9.013	0.00	0.00	0.00	0.00	no
	2	8.589	8.00	8.00	8.00	8.00	no
	3	4.982	6.00	6.00	6.00	6.00	yes
	4	1.773	**5.55**	**5.57**	5.79	5.77[a]	no
	5	1.879	0.50	0.50	0.56	0.56	yes
	6	1.879	0.00	0.00	0.00	0.00	no
Cow Bridge Branch **(68 acres)**	1	11.798	0.00	0.00	0.00	0.00	no
	2	8.548	10.00	10.00	10.00	10.00	no
	3	7.127	7.00	7.00	7.00	7.00	no
	4	4.005	5.39	5.39	5.46	5.46	yes
	5	0.388	4.42	4.42	4.65	4.63[a]	yes
	6	0.07	2.12	2.12	2.18	2.18	no
	7	0	0.43	0.43	0.57	0.57	yes

Notes: Bolded entries indicate an increase in water height due to wetland loss. Blue shading indicates sites for which increased flood heights overlap development. The outlet point heights are heights above sea level.

[a] In some cases, minor decreases in water height are forecast under the 0m wetland depth assumption. This is due to the 10 by 10 meter level at which the analysis forecasts flood levels. More refined spatial data on elevation would decrease this error.

[b] Elevation of land is above the height of the water indicated in this Exhibit. As a result, no development is flooded.

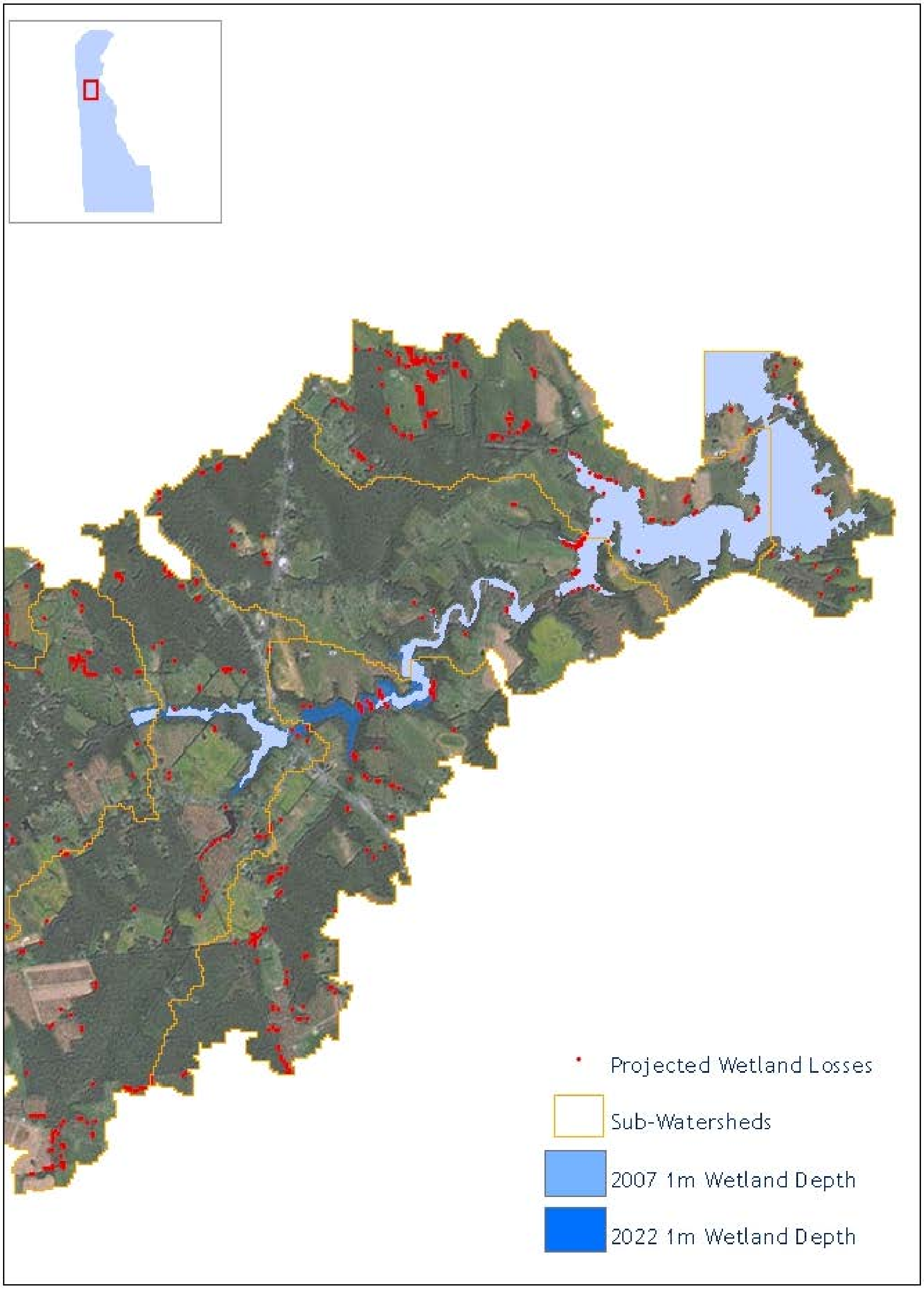
EXHIBIT 37. FLOODED AREA FOLLOWING 25-YEAR, 24-HOUR RAINFALL: RED CLAY CREEK



* Flood extent does not change between 2007 and 2022 scenarios.

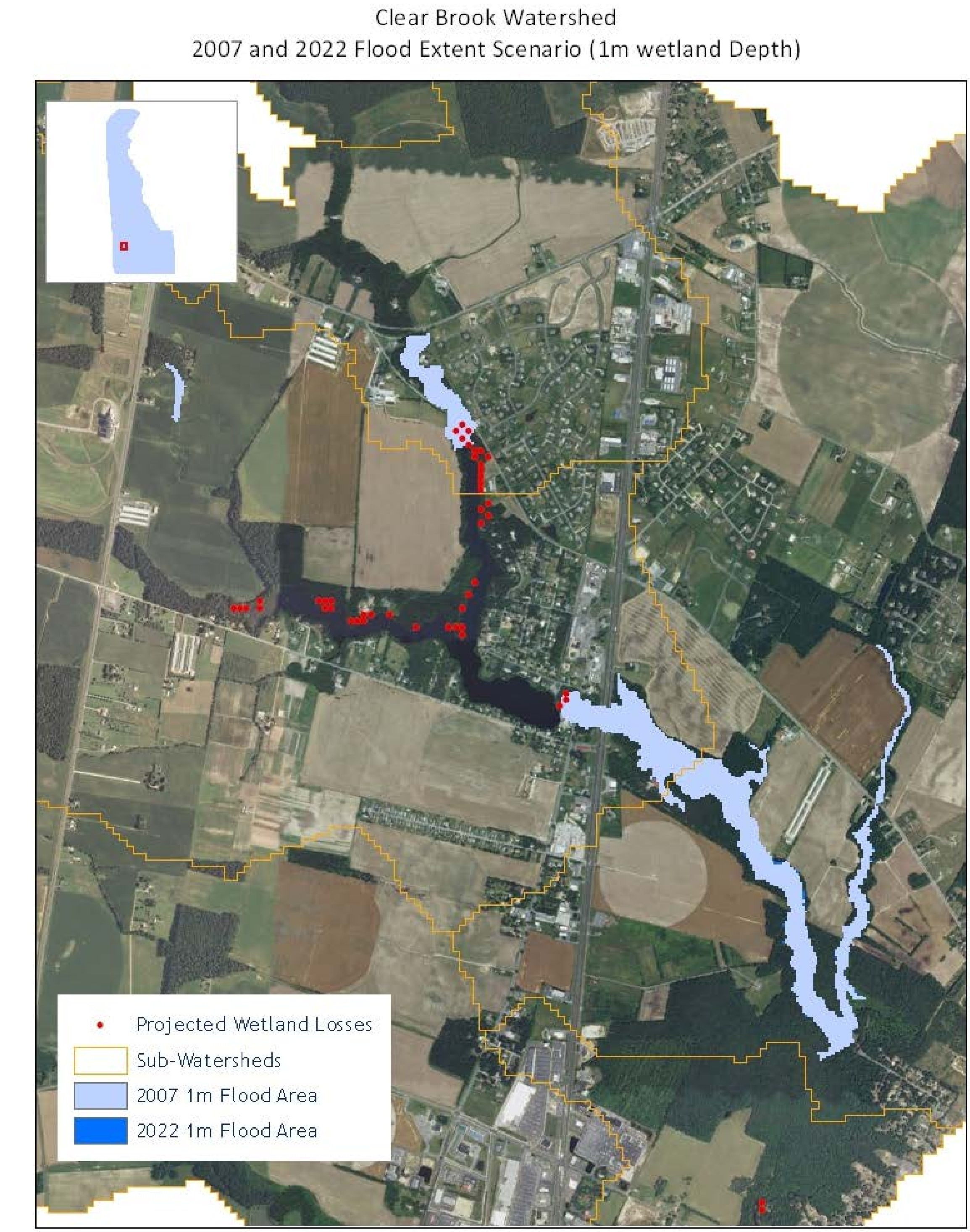
EXHIBIT 38. FLOODED AREA FOLLOWING 25-YEAR, 24-HOUR RAINFALL: BLACKBIRD CREEK

Blackbird Creek Watershed
Runs 1 and 2 for the Flood Area Model (1m Wetland Depth)



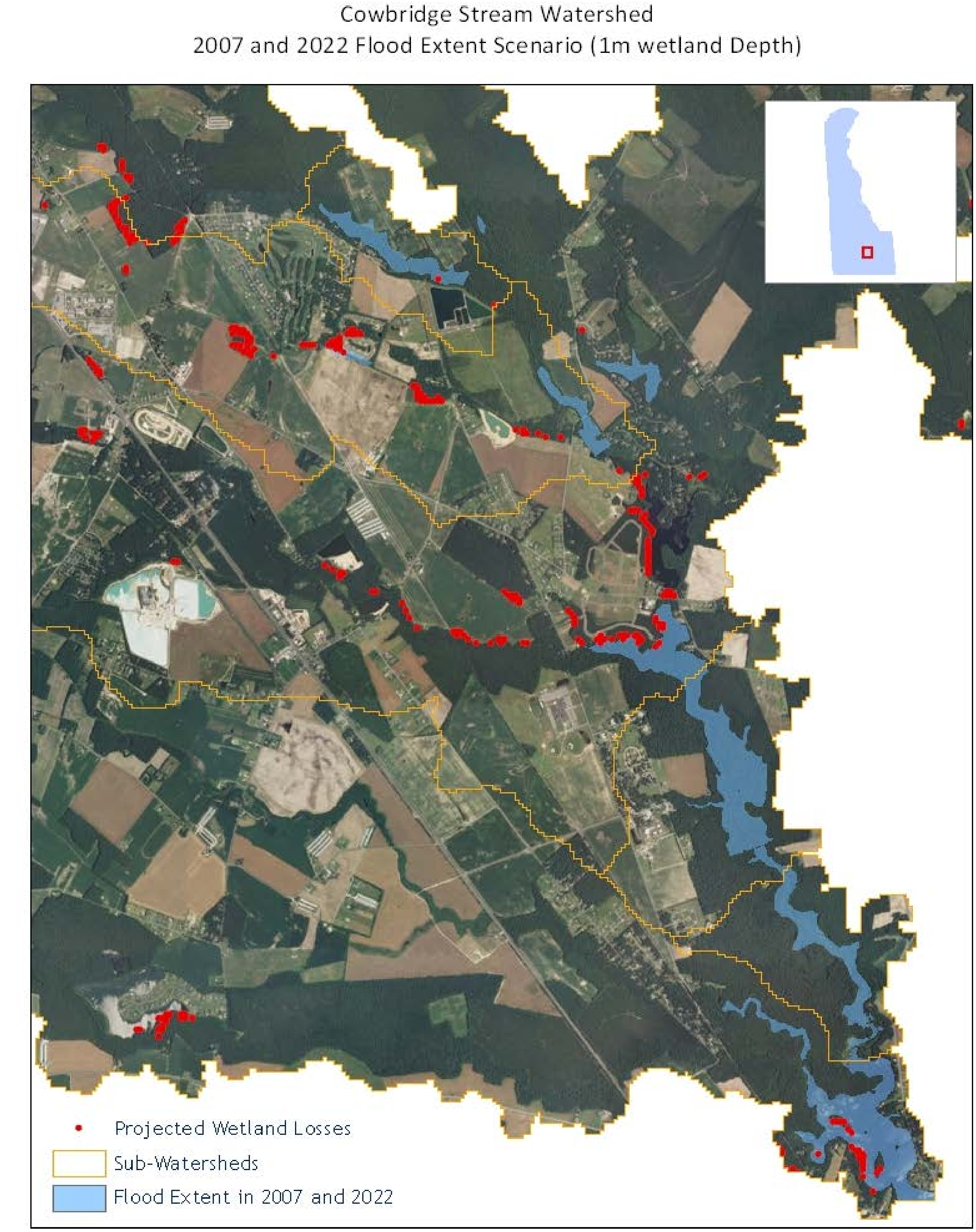
* Changes in flood extent are forecast as intervals along the stream between 2007 and 2022 scenarios.

EXHIBIT 39. FLOODED AREA FOLLOWING 25-YEAR, 24-HOUR RAINFALL: CLEAR BROOK



* Only minor changes in flood extent forecast to occur along edges of flooded area between 2007 and 2022 scenarios.

EXHIBIT 40. FLOODED AREA FOLLOWING 25-YEAR, 24-HOUR RAINFALL: COW BRIDGE



* Flood extent does not change between 2007 and 2022 scenarios.

4.2 COASTAL STORM SURGE MODEL DESCRIPTION AND BIOPHYSICAL CHANGE

The InVEST tool does not yet incorporate a coastal storm surge model.[41] This service is of particular importance in Delaware, however, due to the length of Delaware's coastline, and to the losses of coastal wetlands that buffer properties against flooding. To accompany the inland storm peak model results, we therefore developed a simplified GIS model to simulate potential increases in storm surge associated with loss of coastal wetlands, as follows:

Step 1. Estimate Baseline Coastal Flooding due to a Storm Event

Our analysis is based on DNREC's map of coastal inundation associated with varying sea level rise scenarios. Specifically, DNREC modeled coastal areas likely to be flooded and associated flood heights assuming a sea level rise scenario of mean higher high water (MHHW) plus 1.5 meters in water height.[42] This flooded area served as a proxy for coastal flooding following a storm event. In effect, we assume that a similar area and flood level will result from storm surges of MHHW plus 1.5 meters as from sea level rise of the same level.

While DNREC's GIS maps of the sea level rise scenario are based solely on elevation and do not take into account any armoring, these are the best data available regarding the potential distribution and levels of coastal inundation. To test the reasonableness of our assumption, we compared the sea level rise inundation maps to recent annual coastal storm events recorded by the Delaware Environmental Observing System (DEOS).[43] The sea level rise estimates were within the range of the coastal storm event inundation estimates. We therefore apply these sea level rise scenarios as the baseline coastal flood area and flood heights for our analysis.

Step 2. Quantify the Effectiveness of Wetlands in Attentuating Storm Surge

We were not able to identify any studies specific to Delaware that estimated the value of wetland-related surge attenuation. Such studies are typically focused on areas subject to frequent and intense hurricane surges. We therefore apply an estimate from a recent study of wetland attenuation rates along the Louisiana coastline. The marginal surge attenuation rate associated with wetlands along the Louisiana coast was estimated to be one meter per 13 kilometers.[44] This is the average of four observations of observed attenuation rates due to wetland presence along the coast during Hurricane Rita. Of note, there is a high degree of scatter around this average (estimates range greatly depending on condition of wetland).

[41] The coastal flooding model being developed by the Natural Capital Project is part of Marine InVEST, and is still in the early development stages as of the writing of this report.

[42] Sea level rise shape files provided to IEc by Carl Yetter, Environmental Engineer, Delaware Coastal Programs, DNREC, on November 10, 2010. The maps were developed for each county in Delaware as a representation of inundation based on local Mean Higher High Water. Inundation is assumed to occur at a constant elevation and no other factors other than tidal elevation were used in determining water levels. Delaware Coastal Programs makes no warranty and promotes no other use of these maps other than as a preliminary planning tool.

[43] Leathers, Daniel, J., Robert Scarborough, and David R. Legates. March 2010. A Data GAP Analysis and Inland Inundation Survey for the Delaware Coastline: Final Report and Recommendations. Submitted to the Delaware Department of Natural Resources and Environmental Control. Appendix 8: Inland Inundation Level Data Recorded During Major Coastal Flooding Events.

[44] Wamsley, T.V., et al.. The Potential of Wetlands in Reducing Storm Surge. Ocean Engineering 37 (1) (2010): 59-68.

In addition, a recent meta-analysis regarding wetland-related attenuation rates supports the argument that wetlands provide an important ecosystem service by attenuating surge.[45] The meta-analysis includes three studies of surge-related attenuation rates (one of which is the abovementioned Louisiana study applied in our analysis). The meta-analysis is focused on evidencing that there is a benefit of wetlands in attenuating storm surge, as opposed to pinpointing a best estimate for a transferable attenuation rate. In fact, the study highlights the variation in attenuation rates depending on multiple site-specific factors.

We apply the estimated surge attenuation rate from the Louisiana study as our best estimate as this estimate derives from a study that most closely matches what we are trying to measure. We believe this provides better information that applying an average attenuation rate from multiple different studies designed to model a number of different scenarios (e.g., changes in wetland condition, etc.) in different countries. We chose the attenuation rate estimate that most closely matched our question; specifically, an observed change in storm surge when coastal wetlands are removed based on a U.S. study.

The marginal surge attenuation rate applied in this analysis indicates that storm surge levels decrease by one meter for every 13 kilometers of wetlands passed over. As with the previous analyses, our storm surge analysis divides the landscape into 30 by 30 meter pixels. The attenuation rate therefore translates into roughly a 0.0023 meter decrease in water height for each pixel of wetland the surge crosses.

Step 3. Model the Change in Surge due to Lost Wetlands

Our analysis applies the wetland-related attenuation rates to model the converse: an increase in surge associated with losses in wetlands. That is, to determine where flood levels may increase due to a loss in wetlands, we make the simplified assumption that pixels west of the lost wetland experience the increased flooding. This implicitly assumes that surge primarily travels from east to west. In fact, this surge path is an approximation because as it does not take into account curvature; wetlands may diffuse storm surge energy in other directions.

For each 30 meter pixel of wetland lost, there is an increase in surge of 0.0023 meters. Thus, the greatest change in flood heights occur furthest inland where the surge travels across a greater extent of lost wetland. Exhibit 41 demonstrates the change in surge inland of lost wetlands. The red dots represent the lost wetlands in our 2022 scenario. The gradations of blue dots represent changes in inundation levels west of the lost wetlands. The change in inundation level varies at the 30 by 30 meter grid cell level, ranging from 0.002 meters up to 0.025 meters increase due to lost wetlands along the coast. While these changes are modest, the increase flood levels apply to areas all along the Delaware Bay and Inland Bays coastlines, potentially affecting a significant number of properties, as described in Section 4.3. Exhibit 42 provides a more detailed look at the change in inundation due to wetland losses in a portion of Inland Bays.

---

[45] Gedan, Keryn B., Matthew L. Kirwin, Eric Wolanski, Edward B. Barbier, and Brian R. Silliman. The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm. Climate Change: DOI 10.1007/s10584-010-0003-7. Published online December 14, 2010.

EXHIBIT 41. INCREASED COASTAL STORM SURGE DUE TO PROJECTED WETLAND LOSSES

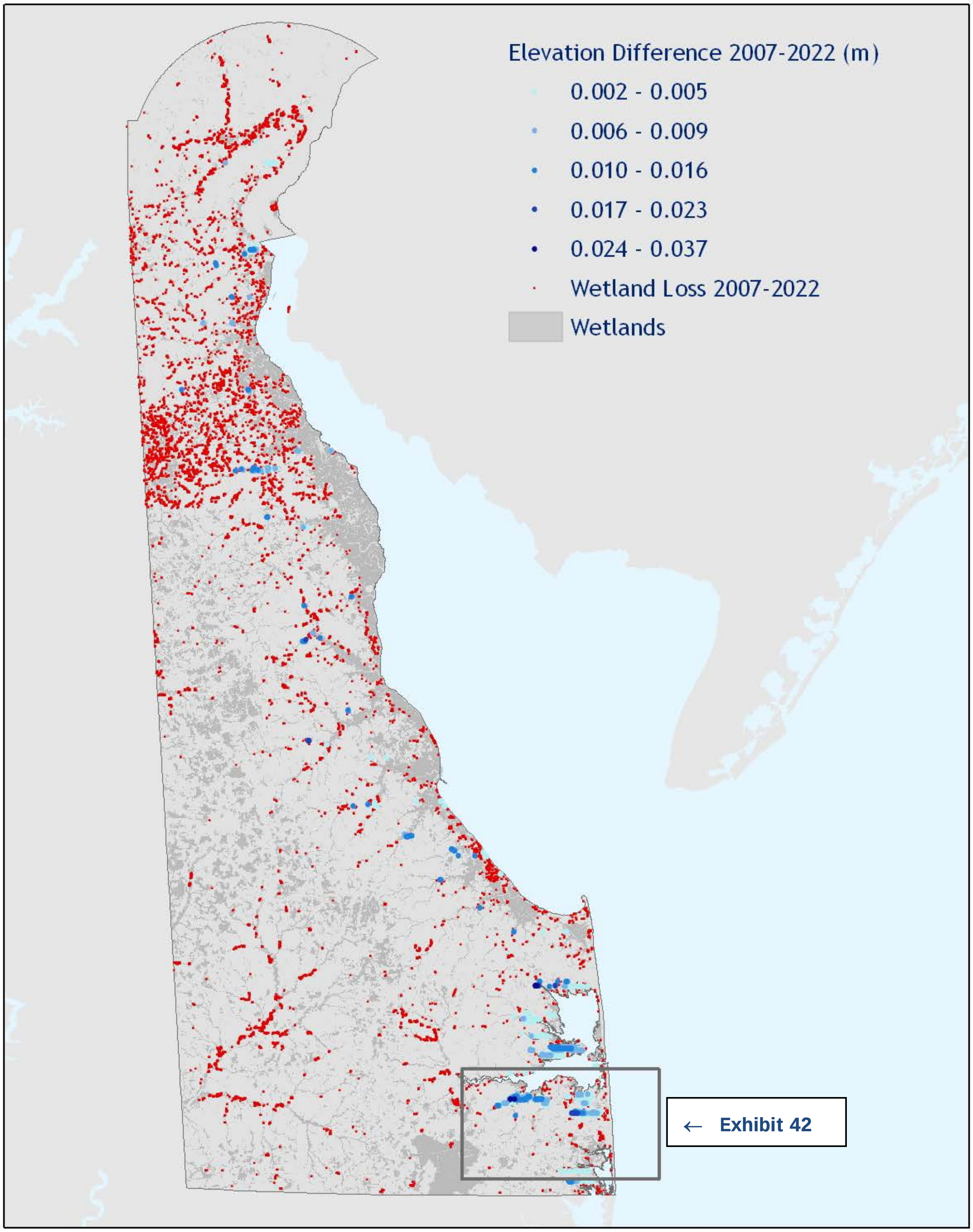
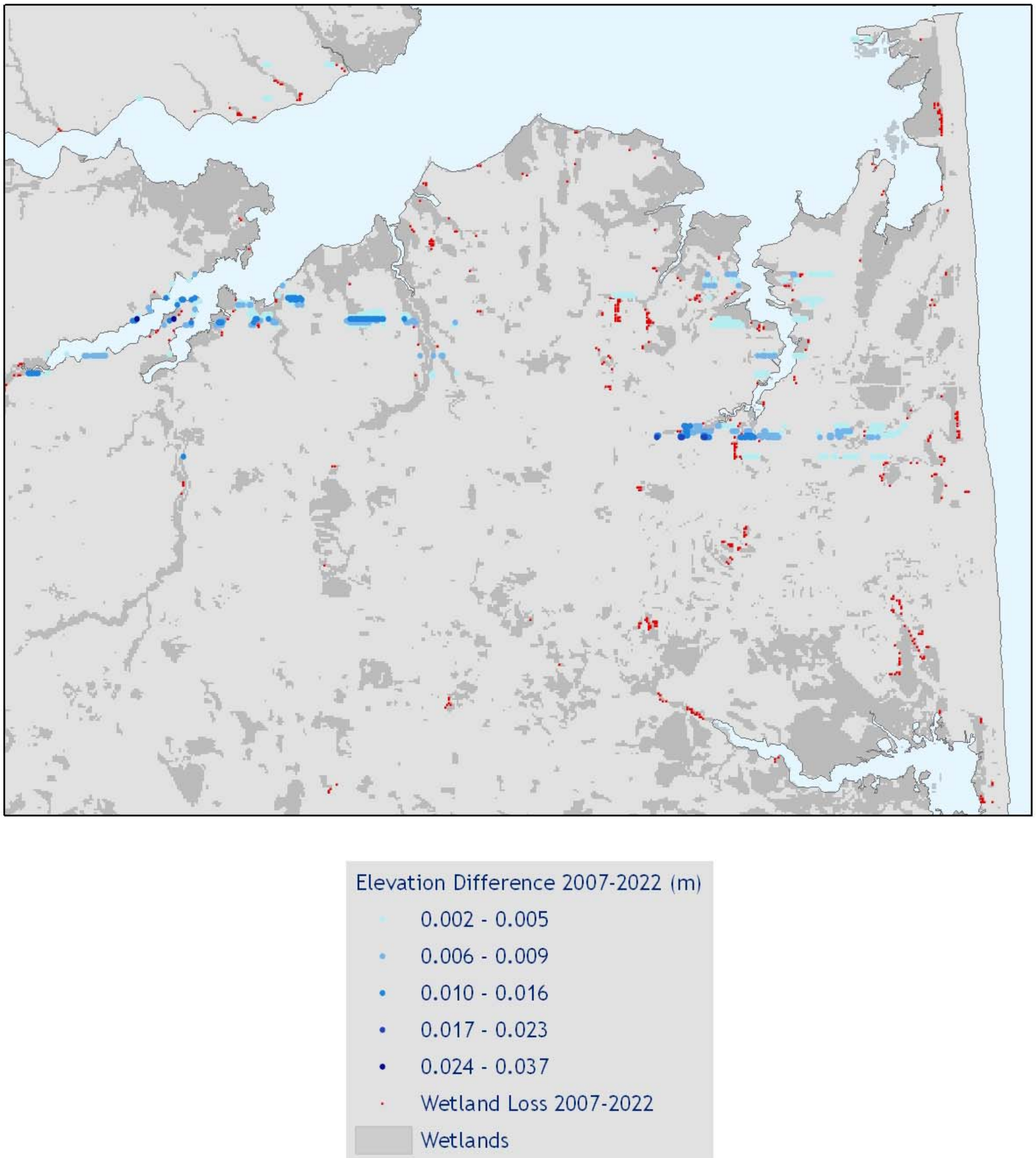


EXHIBIT 42. INCREASED COASTAL STORM SURGE DUE TO PROJECTED WETLAND LOSSES: INLAND BAYS EXAMPLE



4.3 ECONOMIC VALUE

Construction of flood control infrastructure to protect properties can be quite costly, and proper wetland management has proven to be a valuable alternative in some cases. For example, the U.S. Army Corps of Engineers, recognizing the effectiveness of wetlands in mitigating floods, elected to purchase and manage floodplain wetlands along the Charles River in Massachusetts rather than construct flood control infrastructure. The Corps estimated in that case that the loss of 3,400 hectares of wetlands in the basin would increase the costs of flood damages by $17 million per year.[46]

This analysis quantifies the potential economic damages associated with the changes in flood height and extent as described in Sections 4.1 and 4.2. We considered two types of economic damages associated with the incremental flooding: damages to agricultural production (crop damage), and damages to residential development. These are the resources at risk from flooding in Delaware for which we have data to value damages.

Our analysis did not result in incremental damages to crops due to the wetland losses. Generally, crops are considered lost (i.e., full revenue per acre loss) if they experience any flooding. For the most part, the forecast wetland losses resulted in increased flood heights, but not much of an increase in the area flooded. Where there was some increase in area flooded (e.g., around Blackbird Creek), these newly flooded areas did not overlap cropland. Thus, this section focuses on our approach to valuing incremental flood damages to residential development.

Three conditions are required for the wetland losses to result in incremental damages to residential development:

- There is an increase in flood height.
- The area experiencing the increased flood height overlaps residential development structure(s).
- The residential structure(s) in the parcel lies below the height of the flood.

For the inland flooding associated with the 25-year, 24-hour storm event, these conditions are only met in the Red Clay Creek case study and only according to the one meter wetland depth scenario (see Exhibit 36). For the coastal storm surge analysis, we identify benefits to residential infrastructure of wetlands attenuating surge in two drainages: Delaware Bay and Inland Bays. No residential development parcels were affected by increased coastal storm surges in the Chesapeake Bay and Piedmont Drainages. The following steps describe our approach to valuing impacts.

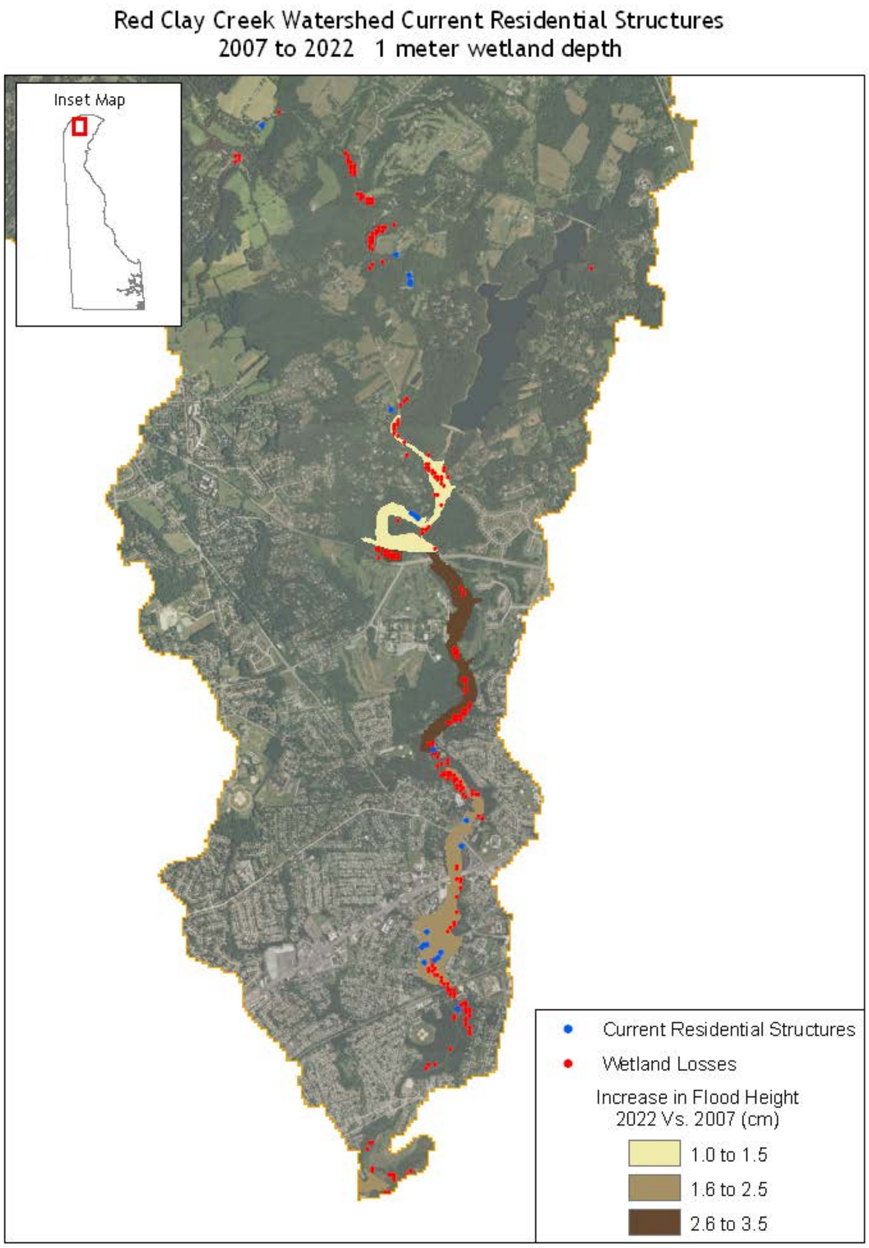
Step 1. Estimate Number and Height of Houses Affected by Increased Flooding

To estimate damages, our analysis requires assumptions regarding how many houses are affected, and the height of the houses off of the ground (i.e., the height at which flood levels no longer infiltrate houses). To estimate the number of affected houses, we apply high and low end estimates.

[46] Mitsch, William J. and James G. Gosselink. Wetlands. Fourth Edition. Hoboken, NJ: John Wiley and Sons, Inc., 2007.

In the Red Clay Creek watershed, we apply specific spatial information developed by New Castle County on the existing residential structures within the 100 year flood plain.[47] The existing residential structures that lie within parcels that experience the incremental flooding represent the low end number (most conservative estimate) of houses affected in our analysis. According to county GIS data, 24 homes currently exist within the area forecast to experience incremental flooding due to wetland losses. These houses are identified in Exhibit 43. Appendix A describes the changes in flood heights in each of the identified structures.

EXHIBIT 43. LOW END ESTIMATE OF THE NUMBER OF HOUSES EXPERIENCING INCREMENTAL FLOODING ALONG RED CLAY CREEK



[47] New Castle County GIS zoning and structures data (ESRI shape files) provided to IEc by Sandra Janowski, New Castle County Department of Administrative Services, GIS and Mapping Services, on March 10, 2011.

At the high end, we apply zoning maps for the Red Clay Creek area to estimate the maximum number of houses potentially flooded assuming full build out of the areas zoned for residential development within the time frame of our analysis.[48] Exhibit 44 describes the New Castle County residential zoning categories that overlap incrementally flooded areas, and the maximum density of houses specified according to the County code. Assuming full build out of the parcels zoned for residential development, 203 houses may overlap the area within Red Clay Creek forecast to experience incremental flooding due to wetland losses. These structures are identified in Exhibit 45. Appendix A describes the forecast changes in flood heights in each of the structures assuming full build out of the areas zoned for residential development.

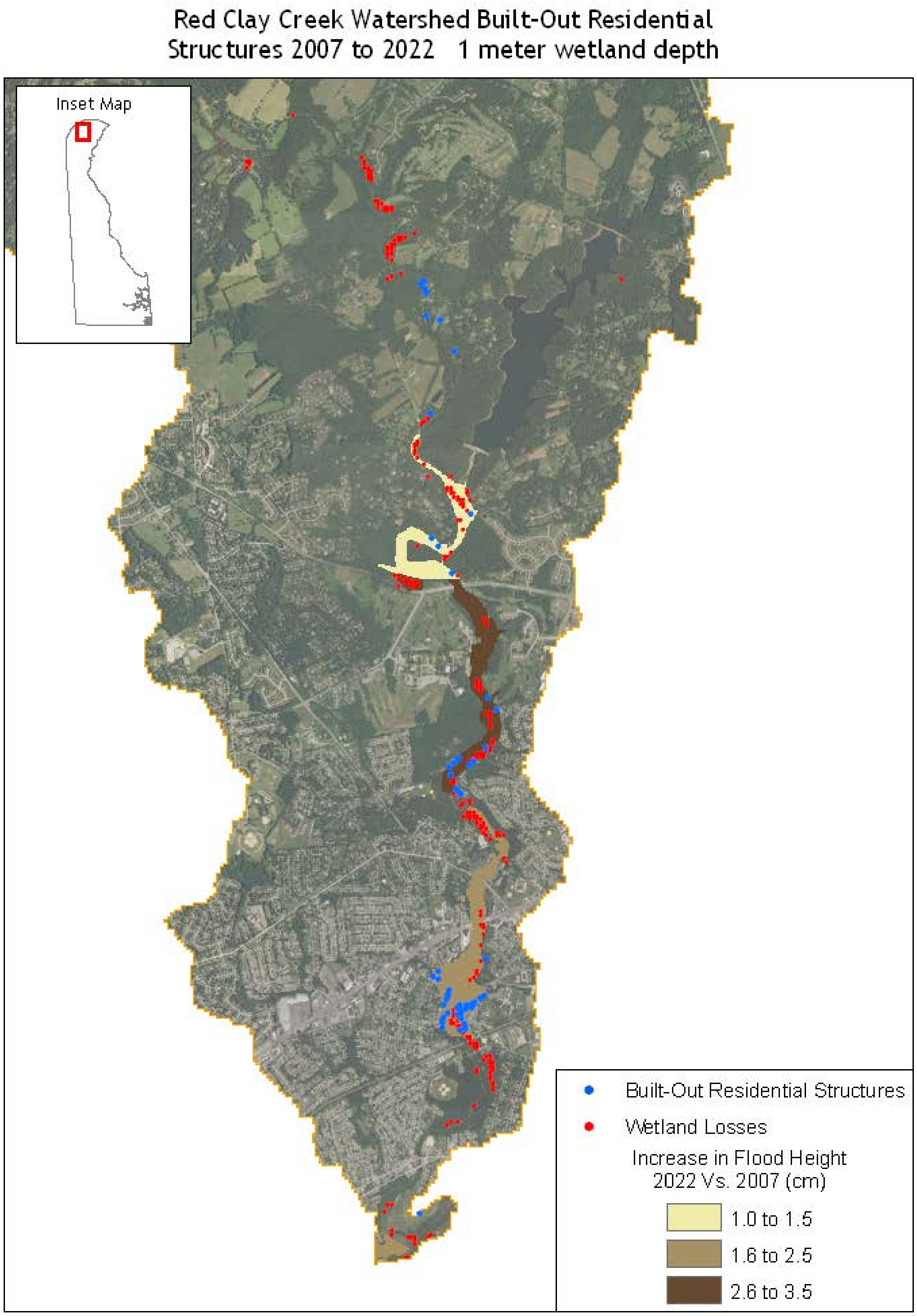
EXHIBIT 44. MAXIMUM HOUSING DENSITIES FOR HIGH END OF AFFECTED HOUSES

ZONING CATEGORY	DESCRIPTION	MAXIMUM HOUSING DENSITY (PER ACRE)
NC15	Single Family - 15,000 square foot lots	1.9
NC21	Single Family - 21,000 square foot lots	1.5
NC2a	Single Family – 2 acre lots	0.4
NC40	Single Family - 40,000 square foot lots	0.9
NC5	Single Family - 5,000 square foot lots	4.6
NC6.5	Single Family - 6,500 square foot lots	3.7
NCap	Apartments	5*
NCga	Garden Apartments	5*
S	Suburban	1
SE	Suburban Estate	0.4
SR	Suburban Reserve	0.3

* Number of apartments at ground level per acre is an estimate.
Source: New Castle County Unified Development Code. Section 40.04.110: District and Bulk Standards.

[48] New Castle County GIS zoning and structures data (ESRI shape files) provided to IEc by Sandra Janowski, New Castle County Department of Administrative Services, GIS and Mapping Services, on March 10, 2011.

EXHIBIT 45. HIGH END ESTIMATE OF THE NUMBER OF HOUSES EXPERIENCING INCREMENTAL FLOODING ALONG RED CLAY CREEK



Absent specific information on the distribution of existing structures in the areas affected in our coastal storm surge analysis, we apply low and high end assumptions based on the number of parcels affected. This analysis relies on GIS data from the counties identifying parcels zoned for residential development. Where the flooded area overlaps the centroid of a parcel zoned for residential development, we assume there is some level of residential development within the parcel that is flooded. At the low end, we assume each residential development parcel includes one house (no matter the size of the parcel). At the high end, we assume two houses per acre are affected. The high end estimate of two houses per acre represents the average of the maximum housing densities for various types of residential development described in Exhibit 44, rounded to the nearest whole house.

While approximately 95 percent of the flooded parcels are less than ten acres, some are quite large (up to more than 300 acres). Assuming future development of these parcels of up to two houses per acre therefore results in a significant range of potentially affected houses. Applying our low and high end assumptions, we estimate between 559 and 3,220 homes may experience incremental flooding assuming houses are 0.30 meters (12 inches) off of the ground. Assuming houses are 0.61 meters (24 inches) from the ground, we estimate between 503 and 3,103 houses will be subject to incremental flooding. Appendix A describes the specific changes in flood height (in meters) in each affected residential development parcel. As indicated in the appendix, the changes in flood heights are quite modest, on the order of 0.025 meters (one inch), due to our wetland loss scenario. This incremental flooding potentially affects many houses, however.

For both inland and coastal flooding, our analysis also employs a range in estimating the height of the lowest floor level of the residential structures above ground level. In our analysis, this represents the height below which flood levels will not affect a property. In other words, we assume flood heights of 0.13 meters (five inches) above ground level do not result in damages to properties situated 0.30 meters (12 inches) above the ground. Due to variations in the foundation heights of homes, we apply the following assumptions:

- **Low end:** Residential structures within the flooded area are 0.30 meters (12 inches) above ground level.
- **High end:** Residential structures within the flooded area are 0.61 meters (24 inches) above ground level.

Of note, these estimates represent our assumption regarding the average height of residential structures aboveground; some residential structures are situated closer to the ground or elevated higher above ground level than the assumed averages. In particular, in coastal areas of Kent and Sussex Counties, it is not uncommon for residential structures to be elevated five feet or more above ground level.[49] In the case that our home height assumptions overestimate the number of homes potentially affected by flooding (i.e. we underestimate the average foundation height of affected homes), our analysis overestimates potential flood damages.

[49] Information provided to IEc by Michael Powell, Delaware Department of Natural Resources and Environmental Control, April 21, 2011.

Step 2. Calculate Damages Per Home as a Function of Flood Height

In order to calculate damages to houses due to incremental flooding, we apply data gathered by the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP) on total damages associated with various flood levels in a 2,000 square foot home.[50] These data are provided in Exhibit 46. We use this information to estimate a functional relationship between flood height and total damages per house.

As described in Exhibit 47, the economic damage function applied to estimate flood damages to residences is logarithmic, beginning to asymptote around flood heights within houses of 1.2 meters (3.94 feet). This means that changes in flood heights above this level are unlikely to affect the estimated economic damages in dollars.

[50] The 2,000 square foot home example does not necessarily reflect homes with a 2,000 square foot footprint only the ground, but rather the total square footage of the residence. The flood damage estimates are based on the appliances, furniture, and other elements likely to be found in a 2,000 square foot home that may be vulnerable to damage from flooding.

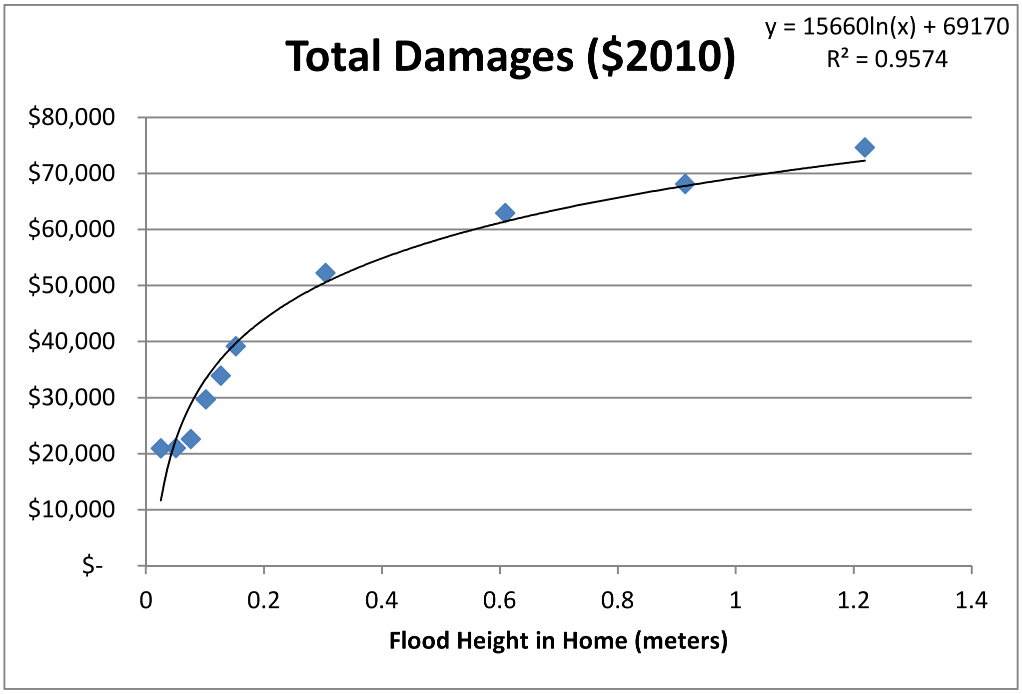
EXHIBIT 46. NFIP DATA ON FLOOD DAMAGES TO RESIDENTIAL HOMES

DAMAGES IN $2010 BASED ON 2000 SQUARE FOOT HOME SAMPLE																			
FLOOD LEVEL	CLEANING	DOORS & BASE TRIM & WINDOWS	ELECTICAL & PLUMBING	FINISHED FLOOR - WOOD - CARPET	INTERIOR WALL FINISHES	WALL INSULATION, DRYWALL OR PANELING	KITCHEN & BATH CABINETS	APPLIANCES	REPARIES TO FURNACE/AC	BEDROOM FURNITURE	DINING ROOM TABLE AND CHAIRS	KITCHEN WARE & FOOD	LIVING ROOM FURNITURE	COMPUTER ACCESSORIES	TELEVISION (2) - DVD - STEREO - ETC.	WASHER/DRYER	ACCENT FURNITURE &ACCESSORIES	LOSS OF PERSONAL ITEMS	TOTAL
1" **(25.4 mm)**	1,700	840	250	15,870			100	130	180	250	230	100	430	80		130	130	500	**20,920**
2" **(50.8 mm)**	1,750	840	250	15,870			130	130	180	250	230	100	430	80		130	130	500	**21,000**
3" **(76.2 mm)**	1,800	890	270	15,870		370	130	130	190	800	400	150	750	80		130	130	500	**22,590**
4" **(102 mm)**	1,850	1,950	290	15,870	1,920	2,910	150	150	200	800	750	200	750	1,100		130	130	500	**29,650**
5" **(127 mm)**	1,900	1,950	300	15,870	1,920	2,910	150	150	210	1,800	1,700	330	2,700	1,100		150	130	600	**33,870**
6" **(152 mm)**	2,000	2,150	320	15,870	1,920	2,910	4,500	180	270	1,800	1,700	330	2,700	1,100	150	150	450	650	**39,150**
1' **(0.30 m)**	2,600	2,150	1,660	15,870	1,920	2,910	4,500	4,200	470	5,500	1,700	730	2,700	1,100	280	980	450	2,500	**52,220**
2' **(0.61 m)**	3,500	2,150	3,000	15,870	1,920	2,910	4,500	4,200	2,200	8,500	2,400	730	3,600	1,100	1,200	980	1,620	2,500	**62,880**
3' **(0.91 m)**	4,100	2,150	3,320	15,870	1,920	3,310	6,100	4,200	2,200	8,500	2,400	830	3,600	1,500	2,000	980	1,620	3,500	**68,100**
4' **(1.22 m)**	4,700	5,150	4,120	15,870	1,920	3,310	6,100	4,200	2,200	8,500	2,400	900	3,600	1,500	2,000	980	1,630	5,500	**74,580**

Note: Estimates are national averages.

Source: FEMA National Flood Insurance Program. Flooding and Flood Risks: The Cost of Flooding. Accessed at http://www.floodsmart.gov/floodsmart/pages/flooding_flood_risks/the_cost_of_flooding.jsp.

EXHIBIT 47. FLOOD DAMAGE FUNCTION



The X axis in Exhibit 47 represents flood height (into the 1st floor) in meters and the Y axis is damage in dollars. As described in Step 1, at the low end, we assume on average houses are 0.30 meters (12 inches) off of the ground; at the high end, we assume they are 0.61 meters (24 inches) from the ground. Thus, according to our low end scenario a 0.33 meter (13 inch) flood height would flood the first floor of a house by 0.025 meters (one inch).

Step 3. Calculate Present Value Impacts over the Time Frame of the Analysis Incorporating the Probability of Storm Occurrance

We apply this function to the estimate incremental changes in flood damages between our 2007 and 2022 scenarios. These incremental damages represent the economic costs associated with the forecast wetland losses.

Inland Flooding at Red Clay Creek

To estimate the present value of damages associated with the 25-year, 24-hour storm event at Red Clay Creek, we first estimate the damages in 2007, and then in 2022, and subtract to estimate the wetland loss impacts in 2022. We assume linear losses in wetlands (and thus linear increases in damages) from such a storm event between 2007 and 2022, with the full impact of our wetland loss scenario occurring by 2022. We then multiply the annual impacts by the probability of the 25-year, 24-hour storm event occurring in each year (i.e., we assign a four percent probability of the storm event occurring in each year). Finally, we apply a three percent social discount rate to quantify the present value of these losses.[51] Exhibit 48 provides the total present value damages to residential structures associated with a 25-year, 24-hour rainfall event due to wetland losses in Red Clay Creek.

EXHIBIT 48. FLOOD DAMAGE IMPACTS ALONG RED CLAY CREEK ($2010)

HOME HEIGHT ASSUMPTION	COST CATEGORY	LOW	HIGH
0.30 m (12 inch)	PV (2007-2022)	$720	$20,500
	Annualized	$57	$1,640
0.61 m (24 inch)	PV (2007-2022)	$958	$21,200
	Annualized	$76	$1,690

As a point of comparison, total NFIP claims paid in 2010 in the State of Delaware were approximately $1.0 million.[52]

The broad range in damages is due to the range in number of houses assumed to be affected by incremental flooding. At the low end, only existing residential structures are affected. At the high end, we assume this area is fully developed and that the additional houses are also affected by the incremental flooding.

That total estimated damages are greater assuming houses are elevated 24 inches off of the ground than assuming they are 12 inches off of the ground is counterintuitive. This result is due to the logarithmic nature of the damage function. An incremental inch of flooding within structures that are flooded between 0.1 and about 0.4 meters results in greater additional damages than an incremental inch of flooding within structures that are flooded between 0.4 and 1.4 meters. This is observable in Exhibit 47. It follows that when the home height assumption is increased, the incremental flooding shifts to the steeper portion of the damage function (i.e., because the houses are higher above ground level, the flood heights within the house are more shallow). This results in greater marginal damage estimates for the additional flooding in a number of the 24 inch houses. This effect is somewhat offset by decreases in total damages due to some houses being projected to be affected by flooding according to the the 12 inch home height assumption, but not the 24 inch home height assumption (i.e., at 24 inches the houses are situated above the flood levels in some areas).

Importantly, these damages reflect the expected value over the 15 year time frame of just one type of storm event with a four percent chance of occurrence in each year. These damages would be additive with the damages associated with other rainfall events. For example, less intense storms may generate fewer damages, but would occur with greater frequency. On the other hand,

[51] For each service-specific analysis, we present economic impacts incurred over time in present value terms. The present value represents the value of a cost or benefit or stream of costs or benefits in common dollar terms. That is, it is the sum of a series of past or future cash flows expressed in today's dollars. We apply a three percent discount rate to calculate the present value impacts, a common social discount rate applied by economists.

[52] State of Delaware National Flood Insurance Program Paid Claims (excel spreadsheet format). Provided to IEc by Micheal Powell, Flood Mitigation Program, DNREC via email on October 11, 2010.

more extreme rainfall events would be associated with greater damages but would have a lower probability of occurrence in a given year.

Furthermore, these estimates reflect only those damages to residential structures along Red Clay Creek. Other types of productive land use (commercial and industrial developments, etc.) may likewise experience damages in this and in other areas of the state. These damages are presented to demonstrate the order of magnitude of one type of damages (residential) at one location (Red Clay Creek). We do not use these estimates as a scalar to calculate damages at the regional or State level. Incremental flooding due to wetland loss is likely to vary significantly by site due to the location of lost wetlands, surrounding land use types, site-specific hydrological processes, and distribution and type of affected development. Simply extrapolating these flood damages to other sites is therefore not appropriate. The estimates presented for Red Clay Creek do, however, provide some perspective on the important role that wetlands play in mitigating flooding.

Coastal Storm Surge Damages

Based on our analysis, wetland losses may increase storm surge levels in the Delaware Bay and Inland Bays drainage. Chesapeake Bay is too far inland to be affected by our scenario (based on DNREC's sea level rise inundation maps) and we do not enough information regarding how water is distributed in the drainage to estimate flooding outside of the sea level rise scenario. While our analysis does indicate some surge in the Piedmont Drainage, incremental flooding associated with the wetland loss scenario is negligible.

To estimate the present value of damages associated with a storm surge of MHHW plus 1.5 meters along the Delaware coast, we first estimate the increased damages in 2022. We then assume linear losses in wetlands (and thus linear increases in damages) from such a storm event between 2007 and 2022, with the full impact of our wetland loss scenario occurring by 2022. We multiply the annual impacts by an assumed probability of this storm event. For the purposes of this analysis, we assume a storm that would result in inundation levels of MHHW plus 1.5 meters would occur approximately once every ten years (i.e., we assign a ten percent probability of the storm event occurring in each year).[53] Finally, we apply a three percent social discount rate to quantify the present value of these losses. Exhibit 49 provides the total present value damages to residential structures associated with a MHHW plus 1.5 meter storm surge due to wetland losses along the Delaware coast.

[53] FEMA Flood Insurance Study (FIS) reports indicate a stillwater elevation ten year return frequency for the Delaware Bay of 5.8 feet (as described by Michael Powell, Flood Mitigation Program, DNREC via email on June 1, 2010). In Delaware Bay, the average elevation of flood heights applying our MHHW plus 1.5 meter flood scenario is approximately 5.4 feet. Absent specific information on flood heights associated with surge events, we therefore assume ten years is a reasonable assumption for the return frequency of a MHHW plus 1.5 meter surge.

EXHIBIT 49. STORM SURGE DAMAGE IMPACTS ALONG THE DELAWARE COAST ($2010)

LOCATION	COST CATEGORY	0.30 M (12 INCH) HOMES ASSUMPTION		0.61 M (24 INCH) HOMES ASSUMPTION	
		LOW	HIGH	LOW	HIGH
Delaware Bay	PV (2007-2022)	$7,340	$69,800	$8,600	$116,000
	Annualized	$585	$5,560	$685	$9,220
Inland Bays	PV (2007-2022)	$40,300	$148,000	$46,000	$185,000
	Annualized	$3,210	$11,800	$3,660	$14,700
STATEWIDE	**PV (2007-2022)**	**$47,600**	**$218,000**	**$54,600**	**$301,000**
	Annualized	**$3,790**	**$17,400**	**$4,350**	**$23,900**

Based on the comparison presented above of total NFIP paid claims of $1.0 million, the estimates, even at the high end, appear reasonable. There is uncertainty, however, regarding multiple factors in this analysis, including the number of potentially affected houses and the probability of this level storm (MHHW plus 1.5 meter surges) occurring in a given year. As with the inland flood analysis, the estimated damages are slightly greater assuming a higher height of houses. While this is counterintuitive, it is due to the logarithmic nature of the damage function, as described above.

4.4 KEY UNCERTAINTIES

Exhibit 50 summarizes the key uncertainties associated with the inland and coastal flooding analyses. These uncertainties are ranked in terms of their significance with respect to the results of this analysis.

EXHIBIT 50. KEY UNCERTAINTIES ASSOCIATED WITH THE INLAND AND COASTAL FLOODING ANALYSES

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES
We modeled only one type of rainfall event (25-year, 24-hour storm event) using the InVEST storm peak model.	**Underestimates** annual inland flooding levels and damages from storm events.	**Major.** The flood damages calculated for this storm event are additive with any other storm events multiplied by their probabilities of occurring in a given year. While less intense storms may result in fewer or negligible damages, they are likely to occur more often. More intense storms may occur less frequently but would likely result in greater damages.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES
We apply the InVEST storm peak model to four case study sites.	**Underestimates** annual inland flooding levels and damages from storm events.	**Major.** Of the four case study sites, two experienced measurable changes in flood heights due to wetland losses. While the extent to which wetland losses affect flooding will vary at other sites, it is very likely that other stream segments will also experience increased flooding and associated damages due to the modeled storm events.
The model specifically considers flooding of properties within the floodplain of rivers and streams at the case study sites.	**Underestimates** annual inland flooding levels and damages from storm events.	**Potentially major.** The model considers only one type of potential flooding in focusing on properties within floodplains of streams and rivers. Additional flooding may occur in the form of "ponding" of stormwater in inland areas.
This analysis focuses on damages to residential infrastructure due to inland flooding and coastal inundation.	**Underestimates** annual inland flooding and coastal inundation levels and associated damages.	**Potentially major.** While we focused our analysis where data were available to estimate damages (i.e., we knew where residential development occurs or may occur in the future and approximate damage estimates of flooding to these structures), other development and productive land use may also be affected by increased flooding. For example, commercial and industrial developments may experience damages from flooding. Likewise parks and recreational developments may be affected. These are not captured in our analysis.
Wetland depths are either all zero or all one meter (low and high end assumptions).	**Overestimates** flooding and associated damages.	**Potentially major.** Wetland depths vary by site. We describe results assuming a broad range in wetland depth. According to our zero meter wetland depth assumption, there is no increase in flooding at our four case study sites due to wetland loss. Our damage results for Red Clay Creek therefore reflect a one meter wetland depth assumption. In fact, flooding and associated damages are more likely to be between these scenarios.
The coastal surge model applies a map of flood depth and area due to sea level rise of MHHW plus 1.5 meters as a proxy for the area potentially flooded by a storm surge of MHHW plus 1.5 meters.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** While DNREC's GIS maps of the sea level rise scenario are based solely on elevation and do not take into account any armoring or other flow path dynamics, these are the best data available regarding the potential distribution and levels of coastal inundation.
The coastal surge model assumes land that lies west of the lost wetlands experiences increased flooding (essentially assuming surge travels from east to west).	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** Data are not available to model curvature to reflect how the surge may travel across the landscape. The effect of alternative assumptions (e.g., that the surge travels shore perpendicular) on the results of the analysis are uncertain.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON VALUE ESTIMATES
Coastal storm surge analysis applies a wetland surge attenuation rate from Louisiana.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** Absent data on the surge attenuation rates associated with wetlands in Delaware, we apply the best available data. These estimates derive from observations of wetland functioning in Louisiana and their applicability to Delaware is significantly uncertain.
We assume frequency of a 25-year, 24-hour storm event in Delaware is once every 25 years.	May **underestimate** flooding and associated damages.	**Potentially major.** Our assumption is that a 25 year storm event occurs once every 25 years. In fact, it is possible that the frequency of these types of storms in increasing.
At the high end, the analysis assumes full build out of areas zoned for residential development.	May **overestimate** flood damages at the high end.	**Potentially major.** The results of the analysis are sensitive to the estimate of affected houses. The assumption of full build out of these areas at the high end may overestimate the number of houses affected in the future. In fact, development of these areas may become increasingly less attractive due to increasing frequency and intensity of flood events over time.
We assume houses are elevated either 0.30 or 0.61 meters (12 or 24 inches) above ground level, and are not affected by flooding below these levels.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Potentially major.** Foundation heights likely vary across the affected area. Newer homes incorporate newer construction guidance for development in a flood plain and are likely to be relatively elevated. Older homes may be more likely to be constructed close to ground level. To the extent that the average home heights are higher on average than the average estimates assumed, our analysis overestimates potential flood damages.
We assume storm events resulting in surge levels of MHHW plus 1.5 meters occur every ten years.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Probably minor.** The probability of such a storm occurring in a given year is unknown. Based on comparison with FEMA FIS reports (see footnote 53), the ten year estimate reflects a reasonable assumption.
Our damage function is based on national average flood damages for a 2,000 square foot home.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Probably minor.** Home size likely varies within the state and the extent to which the national average damage estimates are applicable to Delaware is uncertain. Relative to the other uncertainties, it is unlikely this assumption has a significant effect on the results of the storm peak analysis.
The model InVEST storm peak model assumes that the rain falls at an even rate during the storm event and falls uniformly across the watershed.	**Unknown.** May overestimate or underestimate flooding and associated damages.	**Probably minor.** While rain fall may vary across the landscape, we modeled a relatively targeted area (Red Clay Creek). Relative to the other uncertainties, it is unlikely this assumption has a significant effect on the results of the storm peak analysis.

SECTION 5 | WILDLIFE PROTECTION

Delmarva Fox Squirrel: Photo from DNREC website

Biodiversity, defined as the variability of species and ecosystems within a region, relies on a variety of healthy, functioning habitats. Ecosystems across the State of Delaware have historically supported over 1,000 wildlife species.[54] Wetlands in particular provide habitat for many plant and animal species, and contribute to the health of other key habitats. Loss of wetlands due, for example, to agricultural, residential, or commercial development, may result in direct habitat loss. In addition, conversion of wetland to a non-habitat land use may result in "edge effects" on neighboring habitats. That is, where wetlands are replaced by land uses that fragment or pollute neighboring habitats, broader habitat degradation may occur across the landscape. Maintaining the quality and quantity of habitat in Delaware supports multiple wildlife-related recreation and commercial activities, such as wildlife-viewing, fishing, and hunting. These activities provide recreational opportunities to citizens and tourists, and contribute to the state's economy.

5.1 DESCRIPTION OF MODEL

This analysis applies InVEST to model the effect of our future wetland loss scenario on habitat quality and rarity in Delaware. The model combines spatially-explicit data describing the distribution of key habitat types and the presence of various land use threats (e.g., mining, fire, development) to these habitats to map relative degradation in each drainage across the state. We apply this model first to the status quo in terms of the extent and level of habitat degradation in Delaware. We then model the same parameters in 2022 according to our future wetland loss scenario (described in Section 1). While the extent and degradation of habitats changes over time due to multiple factors, this analysis evaluates specifically how our forecast wetland losses affect the quantity and quality of habitats in Delaware.

[54] Delaware Division of Fish and Wildlife, Delaware Department of Natural Resources and Environmental Control. Delaware Wildlife Action Plan: 2007-2017. September 2006.

The model relies on the following information:

- Spatial distribution of ecologically important habitats across the state (Section 5.1.1);
- Spatial distribution of "threats" particular to each habitat type (Section 5.1.2);
- Maximum distance from habitat at which a threat may degrade habitat (Section 5.1.3); and
- Relative sensitivity of particular habitats to the various threats (Section 5.1.3).

The various habitat types evaluated support myriad plant and animal species. Appendix C lists the Species of Greatest Conservation Need (SGCN) for each habitat type as described by the Delaware Wildlife Action Plan (DEWAP).[55] Importantly, also sensitive plant species stand to be affected by the wetland losses in this analysis, the SGCN lists do not include plant species. While the InVEST model focuses on the impacts of land use threats to the habitats, the species occupying these habitats ultimately experience the repercussions of degradation. For example, reduced quality of habitat for breeding, foraging, and shelter may affect species abundance or richness. In this way, the increases in habitat degradation are representative of the effect of our wetland loss scenario on biodiversity.

Sections 5.1.1 through 5.1.3 describe the data sources applied in this analysis. Section 5.1.4 then describes the analytic framework used to translate these inputs into extent of habitat degradation. Section 5.2 provides the results of our analysis in terms of the change in extent and quality of each habitat type within each of the four main drainages in Delaware, and Section 5.3 discusses the economic implications of these changes. Appendix B includes maps highlighting the geographic distribution of relative habitat degradation across the state for each habitat type. These maps provide information regarding the specific areas within each habitat type forecast to experience the most significant impacts of wetland loss from the evaluated land use threats.[56] Section 5.4 describes the key uncertainties of this analysis.

5.1.1 WILDLIFE HABITAT MAPS

The DEWAP describes key habitat types which, "are rare, have special significance…, are particularly sensitive to disturbance, and/or have a high diversity of rare plants," or are "large blocks of unfragmented forests and wetlands" of at least 250 acres.[57] These habitat types provide the basis for our evaluation. In total, we evaluate 13 habitat categories, grouped according to similarities in ecosystem type and land use threats, as follows:[58]

[55] Appendix C includes only the "Tier 1" SGCN, as described in the DEWAP. The Delaware Division of Fish and Wildlife Service considers these species to be in most urgent need of conservation action. Of note, not all SGCN associated with each habitat type are found in each relevant habitat parcel across the state. For a more complete list of SGCN, including "Tier 2" species, please refer to: Delaware Division of Fish and Wildlife, Delaware Department of Natural Resources and Environmental Control. Delaware Wildife Action Plan: 2007-2017. September 2006.

[56] The gridded maps in Appendix B are provided at a geographic resolution at which the distribution of changes in habitat degradation is visible. This level of detail, however, results in a significant number of individual maps.

[57] Delaware Division of Fish and Wildlife, Delaware Department of Natural Resources and Environmental Control. Delaware Wildlife Action Plan: 2007-2017. September 2006.

[58] This analysis does not evaluate peat wetlands due to the small size of the overall habitat in the state.

- Beach and dune habitat;
- Coastal plain upland forests;
- Early successional habitat;
- Floodplains, swamps, and other forested wetlands;
- Freshwater tidal forest, shrub, and marsh (i.e., “freshwater tidal habitats”);
- Coastal plain seasonal ponds;
- Interdunal swales;
- Piedmont Stream Valley wetlands;
- Non-tidal coastal plain streams, riverine aquatic, and submerged aquatic vegetation (SAV); and
- Tidal high marshes and tidal low marshes (i.e., “tidal marsh”).

Exhibit 51 describes the sources employed to map each of the above habitat types. The habitat data sources in Exhibit 51 identify the “communities” mapped by DNREC that correspond to habitats described in the DEWAP. In most cases, the mapped community matches the description of habitat type. In order to accurately capture the full extent of other habitat types, we augmented the DEWAP data with additional information on land use in the state.

EXHIBIT 51. DELAWARE KEY WILDLIFE HABITATS

HABITAT TYPE	HABITAT DATA SOURCE
Beach and dune habitats	"Beach and Dune Communities"[a]
Coastal plain upland forests	Includes areas where identified "Forest Blocks" habitat[a] overlap identified "Forest" land uses[b]
Early successional habitats	"Early Successional Habitat"[a]
Floodplains, swamps, and other forested wetlands*	Includes both "Atlantic White Cedar Non-tidal Wetlands"[a] and identified "Flat" wetlands[c]
Freshwater tidal habitats	Includes "Freshwater Tidal Forested," "Shrub-Scrub Wetlands" and "Mixed Broadleaf Freshwater Tidal Marsh"[a]
Coastal plain seasonal ponds	"Coastal Plain Seasonal Pond"[a]
Interdunal swales	"Interdunal Wetland"[a]
Piedmont Stream Valley wetlands	"Piedmont Stream Valley Wetland"[a]
Non-tidal coastal plain streams, riverine aquatic and SAV	Includes both "Non-tidal Coastal Plain Streams" and "Riverine Aquatic and Submerged Vegetation"[a]
Tidal marshes	Includes identified "Tidal Marsh"[c], excluding overlap with "Freshwater Tidal Forested" habitat[a]

Sources:
[a] IEC_Ecosystem_Services_Key_Wildlife_Habitats [ESRI Shapefile]. Dover, Delaware: Karen Bennett, Program Manager Natural Heritage, Endangered Species & Private Lands Programs, DE Division of Fish and Wildlife. Emailed to IEc February 9, 2011.
[b] Land uses defined in: Sanborn Map Company, Inc. 2007 Delaware Land Use and Land Cover [ESRI Shapefile]. 1st Edition. State of Delaware, Office of Management and Budget, Delaware Geographic Data Committee. 2007.
[c] Delaware 2007 NWI GIS Shapefile: McGuckin, K. 2011. Methods Used to Create Datasets for the Delaware State Wetlands Update. Conservation Management Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA.
Note: *Absent an explicit Key Wildlife Habitat mapping of this habitat type, we approximated the distribution of his habitat across the state according to guidance provided by DNREC.

5.1.2 HABITAT THREATS

Habitats in Delaware are exposed to a number of threats, ranging from shoreline protection practices and recreation, to expansion of development and invasive species. These conservation threats individually and in aggregate compromise the ability of habitats to recover from injury and to provide for species. This analysis focuses on land use threats described in the DEWAP for which spatial data are available to describe the distribution in each drainage across the state. Specifically, we map the following habitat threats:

- Residential, commercial, and industrial development;
- Agricultural development and operations;
- Transportation and utility infrastructure;
- Fire regimes;
- Recreational activities; and

- Mining.

These land uses threaten habitat quality either by directly replacing habitat (habitat loss), reducing the continuity of habitats (habitat fragmentation), or introducing sources of pollution, pathways for predators and invasive species, or other disturbances to neighboring habitat (edge effects).

Of note, this is not a comprehensive list of all threats to habitats within the state. Spatial information is more limited for certain threats, such as the presence of invasive species, hydrology alternations, sea level rise, and dredging activities. While not explicitly mapped and evaluated in this analysis, we do not assume these activities do not degrade habitat. Excluding these threats does, however, implicitly assume that the extent of habitat threat associated with these activities is not affected by our future wetland loss scenario. In other words, continued wetland decline through 2022 does not alter the impact of these threats on the level of habitat degradation in this analysis.

Exhibit 52 describes the data applied to represent the presence of the evaluated threats across the state.

EXHIBIT 52. DELAWARE HABITAT THREATS ASSESSED

THREAT TYPE	THREAT DATA SOURCE
Residential and Commercial Development Practices	Single Family Dwellings, Multi Family Dwellings, Mobile home Parks/Courts, Commercial, Mixed Urban or Built-up Land, Institutional/Governmental[a]
Agricultural Operation	Farms, Pasture and Cropland, Confined Feeding Operations/Feedlots/Holding[a]
Industrial Development and Operation	Industrial[a]
Transportation and Utility Operations and Maintenance	Delaware Roads[b]
Changes in Fire Regimes	Phragmites[c] and Young Loblolly Pine stands[d]
Recreational Activities	Recreational[a]
Mining	Extraction and Transitional[a]

Sources:

[a] Land uses defined in: Sanborn Map Company, Inc. 2007 Delaware Land Use and Land Cover [ESRI Shapefile]. 1st Edition. State of Delaware, Office of Management and Budget, Delaware Geographic Data Committee. 2007.

[b] DE_CENTER_LINE [ESRI Shapefile]. Dover, Delaware: Delaware Department of Transportation, 2002. Available: http://www.deldot.gov/information/pubs_forms/gis/centerline/index.shtml (July 1, 2010).

[c] Delaware_Fuel_Model_3 [ESRI Shapefile]. Dover, Delaware: Glenn Gladders, Delaware Department of Agriculture. Emailed to IEc August 26, 2010.

[d] Delaware_Pine_Plantations_clip [ESRI Shapefile]. Dover, Delaware: Glenn Gladders, Delaware Department of Agriculture. Emailed August 26, 2010.

5.1.3 SENSITIVITY AND DISTANCE

This analysis assumes habitat quality is a function of the habitat's proximity to the land use threats, and to the relative sensitivity of each habitat type to each land use threat. The more sensitive a habitat is to a land use threat, the more degraded the habitat will be when the threat is present. To account for the relative impact of the land use threats, the model relies on a score of the habitat's "sensitivity" to the various threats. The sensitivity of habitat to these threats varies within and across habitat types. For example, beach and dune habitats are more sensitive to degradation from recreation activities than, for example floodplains and swamps. Additionally, recreation activities are likely more degrading than transportation projects to beach and dune habitat.

Exhibit 53 describes the sensitivity scores for each habitat type to each threat. For each habitat type, the threats are assigned a sensitivity score of zero to one. These scores are normalized such that the sum across threats within a habitat type is equal to one. A sensitivity score of 0.5 for a threat indicates that the habitat type is twice as degraded by the presence of that threat than the presence of a threat scored as 0.25, all else equal.

Exhibit 53 also provides information on the maximum distance at which a threat will degrade a habitat. As previously noted, the impact of a threat attenuates over space. In other words, habitat grid cells closer to threats will be more degraded by the threat than those further away. Our analysis assumes that the level of degradation decreases exponentially with distance from the threat (i.e., we apply an exponential distance-decay function, as described in Section 5.1.4). The maximum distance values indicated in Exhibit 53 describe the distance beyond which a threat no longer degrades a habitat grid cell.

A team of biologists and ecologists from the DNREC's Division of Fish and Wildlife determined the sensitivity scores and distances described in Exhibit 53. These parameters are multiplied to determine the overall level of degradation introduced by these land use threats for each habitat grid cell, as described in Section 5.1.4. The absence of sensitivity scores and distances for a particular threat indicates that the DEWAP does not specify the threat is relevant to the habitat type.

EXHIBIT 53. HABITAT SENSITIVITY TO THREATS

HABITAT TYPE		THREATS						
		DEVELOPMENT	AG/FORESTRY	INDUSTRIAL	UTILITIES/ ROADS	RECREATION	FIRE	MINING
Beach and dune	Sensitivity	0.15		0.15	0.20	0.50		
	Distance (km)	0.25		0.25	0.25	0.25		
Coastal plain upland forest	Sensitivity	0.38	0.21	0.13	0.17	0.04	0.07	
	Distance (km)	0.25	0.25	0.25	0.25	0.10	0.25	
Early successional habitat	Sensitivity	0.40	0.18	0.15	0.15	0.02	0.10	
	Distance (km)	0.10	0.10	0.10	0.10	0.10	0.10	
Floodplains, swamps, and other forested wetlands	Sensitivity	0.36	0.29	0.16	0.13	0.03	0.03	
	Distance (km)	0.25	0.25	0.25	0.25	0.25	0.25	
Freshwater tidal habitats	Sensitivity	0.35	0.30	0.19	0.16			
	Distance (km)	0.25	0.25	0.25	0.25			
Coastal plain seasonal ponds	Sensitivity	0.32	0.32	0.12	0.12	0.05		0.07
	Distance (km)	0.25	0.25	0.25	0.25	0.25		0.25
Interdunal swales	Sensitivity	0.46	0.00	0.13	0.19	0.22		
	Distance (km)	0.25		0.25	0.25	0.25		
Piedmont Stream Valley wetlands	Sensitivity	0.42	0.19	0.12	0.27			
	Distance (km)	0.25	0.25	0.25	0.25			
Non-tidal coastal plain streams, riverine aquatic, and SAV	Sensitivity	0.31	0.33	0.12	0.17	0.08		
	Distance (km)	0.25	0.25	0.25	0.25	0.25		
Tidal marsh	Sensitivity	0.36	0.32	0.13	0.14	0.06		
	Distance (km)	0.25	0.25	0.25	0.25	0.10		

Source: EIC_Threats_Averages [Excel File]. Dover, Delaware: Amy Jacobs, Delaware Department of Natural Resources and Environmental Control. Emailed to IEc January 10, 2011.

5.1.4 ANALYTIC FRAMEWORK

Overview

To determine the change in extent and level of habitat degradation due to our wetland loss scenario, we model the overall level of degradation for:

1. **The baseline scenario:** This is the current distribution of wetlands, habitats, and land use threats across the state; and
2. **The future scenario:** This reflects the hypothetical wetland loss scenario 15 years into the future, as described in Section 1 of this report. All other land uses and threats are held constant.

For each scenario, we first develop a raster map of each habitat type. The raster maps divide the habitat into 30 meter grid cells. We likewise map each of the land use threats at a 30 meter grid cell level. The analysis therefore estimates the level of degradation within each habitat type at this level of geographic resolution.

For each habitat grid cell we calculate an overall degradation level as a function of: 1) the number of threats affecting the grid cell (i.e., the number of threats within the minimum threat distance identified in Exhibit 53); 2) the sensitivity of the habitat to the various threats; and 3) the distance of the threat from the grid cell. We then estimate the overall level of degradation for the entire habitat area within each drainage by summing the overall degradation scores of the individual habitat grid cells.

The difference in habitat extent and degradation between these two scenarios represents the impact of the forecast wetland losses. Under our future scenario, wetlands are lost to land uses such as development and agriculture. As described in Section 5.1.2, these land uses are considered threats to particular habitat types.[58] The impact of wetland losses on habitats is therefore twofold:

- **Direct habitat loss,** expressed in acreage and percent, occurs in cases where the wetland itself was part of a habitat; and
- **Increased habitat degradation** (i.e., edge effects**),** expressed as percent change, on neighboring habitats where the new land use threat occurs within the distance threshold described in Exhibit 53.

Thus, our analysis determines both habitat loss and increased degradation for each habitat type, as follows.

Step 1. Calculate Impacts of each Threat for each Habitat Grid Cell

The first step is to calculate the effect of each individual threat on a habitat grid cell. A habitat grid cell may not experience any impact from the threats (i.e., none of the above threats are

[58] Of note, we do not attempt to forecast potential increases in utilities, roads, and other infrastructure that may accompany the conversion of wetlands to development. This may lead to an underestimate of the increased threat to habitats associated with developed wetlands. We do not anticipate excluding these factors has a major effect on our results, however, as one factor in forecasting wetlands that may be developed is proximity to existing infrastructure to support the development.

identified within the relevant distance thresholds), or be subject to multiple different threats (i.e., multiple threats are identified within the relevant distance thresholds).

As noted above, we assume that the impact of a threat on a habitat grid cell decreases exponentially with distance. Thus, the impact of a threat over distance is expressed as: [59]

$$i_{rxy} = \exp[-(2.99/d_{rmax})d_r]$$

Where:

i_{rxy} = The impact of threat *r* as a function of the distance from threat grid cell *y* to habitat grid cell *x*.

d_{rmax} = The maximum effective distance of threat *r* (see Exhibit 53).

d_r = Linear distance between threat grid cell *y* and habitat grid cell *x* (i.e., the distance from the habitat to the threat source).

As such, all else equal, grid cells closer to threats experience greater degradation effects.

In addition to distance, we factor in the sensitivity of the habitat to the various threats (see Exhibit 53). The distance impact and sensitivity are multiplied together to estimate the level of degradation for a single threat source on a single habitat grid cell, as described in the following expression:

$$D_{jxy} = i_{rxy} * S_{jr}$$

Where:

D_{jxy} = Partial degradation score for a given grid cell x of habitat j due to the presence of threat grid cell y.

S_{jr} = Sensitivity of habitat type j to threat r (Exhibit 53).

Step 2. Calculate Total Degradation Level of Each Grid Cell

As noted above, each grid cell of habitat may be subject to multiple threats. In order to estimate the total degradation score associated with a habitat cell, we must therefore sum across the various threats, as follows:[60]

$$D_{jx} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} (r_y * i_{rxy} * S_{jr})$$

Where:

D_{jx} = Total degradation score for a given grid cell *x* of habitat *j*.

j = Habitat type (as described in Exhibit 51).

---

[59] The Natural Capital Project. InVEST 1.004 Beta User's Guide: Integrated Valuation of Ecosystem Services and Tradeoffs. Ed. Heather Tallis and Taylor Ricketts. 2009.

[60] *Ibid.*

r = Threat type (as described in Exhibit 52).

R = the full suite of habitat threats (as described in Exhibit 53).

x = Habitat grid cell.

y = Threat grid cell.

Y_r = Total number of grid cells representing threat *r*.

r_y = Binary variable indicating the presence/absence of threat *r* in grid cell *y* (0 or 1).

S_{jr} = Sensitivity of habitat type j to threat r (as described in Exhibit 53).

The first summation in this expression sums all threat grid cells of a particular threat type. In other words, if four "developed" grid cells fall within 0.25 kilometers of a beach and dune habitat grid cell, the partial degradation scores associated with the presence of all four threat cells are summed. The second summation sums across multiple threat types (e.g., development, recreation, etc.).

Exhibit 54 provides an example calculation of this process for a single habitat grid cell, x, under both the baseline (2007) and future (2022) scenarios. In this example, the habitat cell is affected by the presence of two threats under the baseline scenario (y1 and y2), and three under the future scenario due to a developed wetland (y3).

EXHIBIT 54. EXAMPLE CALCULATION

Calculation of degradation score on one habitat grid cell (*x*) with sensitivity to different threats (S_{jr}), assuming 0.25 km maximum effective distance (d_{rmax}) for all threats.

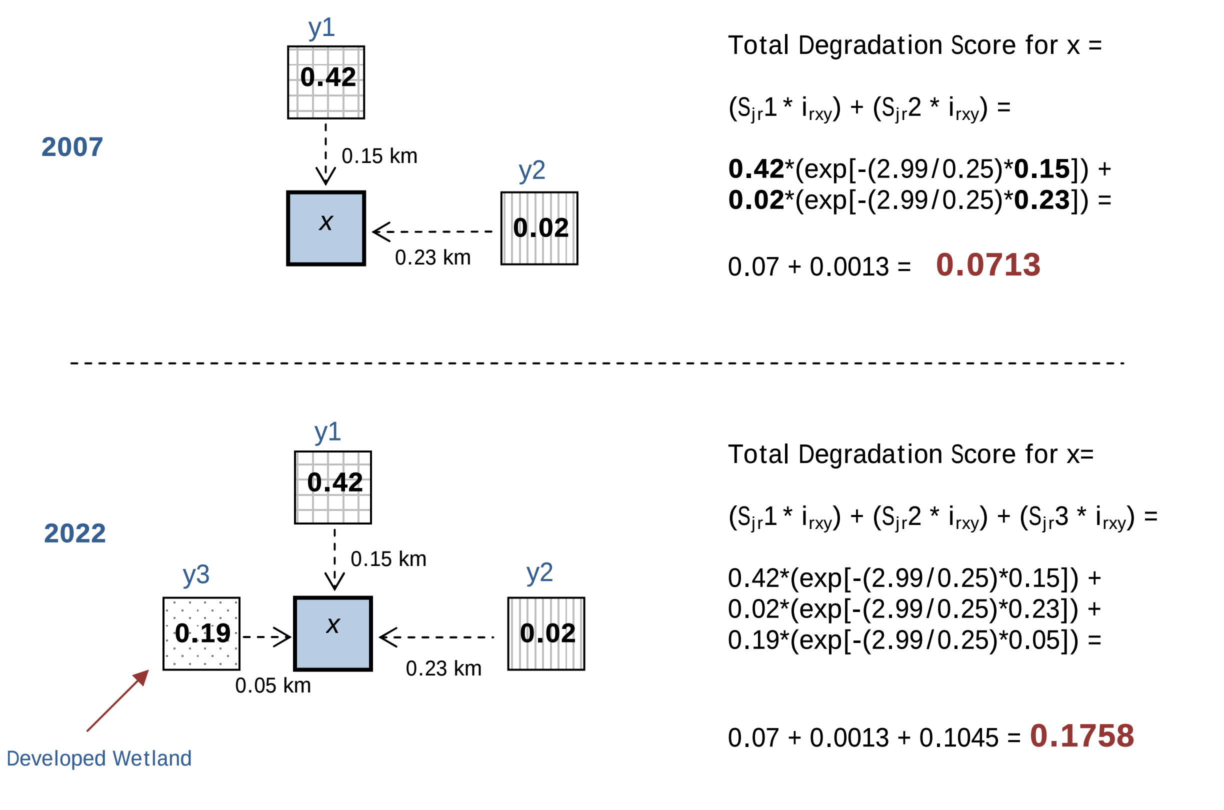


Exhibit 54 describes a habitat grid cell relatively close to a developed wetland. In this case, the increase in degradation score for the grid cell is about 147 percent. Habitat grid cells further away from the developed wetland would be less affected by the introduction of this threat, and habitat grid cells more than 0.25 kilometers from the developed wetland would not be affected.

We present both the 2007 and 2022 scenarios in this example because the key indicator of the effect of the wetland loss is not the change in degradation score, but the percent change in level of degradation. The degradation scores are nominal rankings of the threats to a particular habitat type and are unitless. They can be compared within a habitat type but *cannot be compared across habitat types*. The percent change in habitat degradation indicates impact of the wetland losses on habitat quality beyond the baseline level of degradation.

Step 3. Calculate Overall Habitat Acreage and Degradation Level for each Habitat Type

Next, we calculate the extent of habitat (total acres of habitat) and total degradation scores for each habitat separately under the baseline and future scenarios. The habitat acreage is derived from the habitat maps. The only changes in acreage within a habitat type are due to the forecast wetland losses. Therefore, habitat types that do not include wetlands do not experience habitat loss in this analysis.

To calculate total degradation level for habitat types, we sum the degradation scores of all pixels within a habitat type. The wetland losses affect degradation levels in the closest habitat grid cells (e.g., as described in Step 1, the impact of a threat on a habitat cell decreases exponentially with distance up to a maximum effective distance of 0.25 km).

Step 4. Estimate Change in Extent and Level of Habitat Degradation Due to Wetland Losses

Finally, we determine the effect of wetland losses on habitat degradation by subtracting the habitat acreages (to determine habitat loss) under the baseline and future scenarios, and calculating the percent change in degradation scores across habitats. The percent difference in scores can be interpreted as the increase in the degradation level of the remaining habitat in 2022. For example, if a habitat in 2022 has a combined degradation score of 3,500, and the same habitat area had a score of 3,250 in 2007, the percent increase in degradation of the overall habitat type is predicted to be 7.6 percent.

5.2 BIOPHYSICAL CHANGE

Exhibit 55 provides the overall results of the analysis for each habitat type within each of the four major drainages. As described above, the percent change in habitat-wide degradation is a function of the degradation scores of all individual habitat grid cells. A portion of those grid cells will not experience a change in degradation score between the baseline and future scenarios (i.e., degradation scores do not change for grid cells further from the maximum effective distance of the developed wetland). As a result, the overall percent changes in level of degradation for a habitat type range from zero to almost ten percent.

Exhibit 55 provides an overview of habitat loss and degradation in each drainage across the state in percentage terms. Section 5.2.1 through 5.2.4 provide more detailed results of the analysis by drainage. These sections describe the greatest habitat losses (in terms of acreage) and degraded habitat (in terms of percentage increase in degradation level) by drainage. Importantly, because not all habitat threats are mapped and accounted for, these estimates are best considered in relative terms to identify those habitats at greatest risk from future wetland loss. Appendix B provides detailed maps of the change in habitat degradation for each habitat type. These maps demonstrate the distribution of affected habitat in relative terms.

EXHIBIT 55. EFFECTS OF FORECAST WETLAND LOSS ON HABITAT EXTENT AND DEGRADATION

HABITAT TYPE		PIEDMONT DRAINAGE	DELAWARE BAY DRAINAGE	CHESAPEAKE BAY DRAINAGE	INLAND BAYS DRAINAGE
Beach and dune	Presence of Habitat in Drainage in 2007 (%)	0.0	**0.6**	0.0	6.6
	Habitat Loss (%)	-	**2.46**	-	0.85
	Increase Degradation (%)	-	**0.49**	-	0.28
Coastal plain upland forest	Presence of Habitat in Drainage in 2007 (%)	31.0	12.8	20.1	26.1
	Habitat Loss (%)[a]	N/A	N/A	N/A	N/A
	Increase Degradation (%)	0.45	**0.74**	0.61	0.24
Early successional habitat	Presence of Habitat in Drainage in 2007 (%)	27.8	**8.4**	**9.5**	6.0
	Habitat Loss (%)	0.17	**0.18**	0.02	0.09
	Increase Degradation (%)	0.07	0.10	**0.16**	0.14
Floodplains, swamps, and other forested wetlands	Presence of Habitat in Drainage in 2007 (%)	**21.2**	18.6	65.0	33.6
	Habitat Loss (%)	**5.58**	2.32	0.55	0.98
	Increase Degradation (%)	**2.18**	1.39	0.66	0.28
Freshwater tidal habitats	Presence of Habitat in Drainage in 2007 (%)	**10.3**	6.2	0.4	0.2
	Habitat Loss (%)	**4.14**	2.21	3.63	0.69
	Increase Degradation (%)	**8.42**	2.49	4.10	0.41
Coastal plain seasonal ponds	Presence of Habitat in Drainage in 2007 (%)	**0.4**	0.5	**0.3**	0.1
	Habitat Loss (%)	**2.27**	1.58	2.12	0
	Increase Degradation (%)	1.29	0.97	**5.08**	0.59
Interdunal swales	Presence of Habitat in Drainage in 2007 (%)	0.0	0.0	0.0	**0.2**
	Habitat Loss (%)	**-**	**-**	**-**	**7.34**
	Increase Degradation (%)	-	-	-	**0.63**
Piedmont Stream Valley wetlands	Presence of Habitat in Drainage in 2007 (%)	**1.0**	0.0	0.0	0.0
	Habitat Loss (%)	**0.68**	-	-	-
	Increase Degradation (%)	**0.85**	-	-	-

HABITAT TYPE		PIEDMONT DRAINAGE	DELAWARE BAY DRAINAGE	CHESAPEAKE BAY DRAINAGE	INLAND BAYS DRAINAGE
Non-tidal coastal plain streams, riverine aquatic, and SAV	Presence of Habitat in Drainage in 2007 (%)	**3.6**	1.7	4.7	3.9
	Habitat Loss (%)[a]	N/A	N/A	N/A	N/A
	Increase Degradation (%)	**2.00**	0.89	0.48	0.13
Tidal marsh	Presence of Habitat in Drainage in 2007 (%)	0.0	51.2	0.0	23.4
	Habitat Loss (%)	-	0.45	-	1.15
	Increase Degradation (%)	-	1.29	-	2.55

Notes: A "-" symbol indicates that the habitat type is not present within the drainage. Numbers in bold indicate highest loss and degradation for each habitat.

[a] Coastal plain upland forest and non-tidal coastal plain streams, riverine aquatic, and SAV habitat types are not projected to experience habitat loss. This is because the projected habitat losses are all associated with wetland habitat types. In other words, the wetland losses forecast in this analysis equate to losses across various habitat types. Because coastal plain upland forests and non-tidal coastal plain streams, riverine aquatic, and SAV habitats are not wetland habitats, they do not experience habitat losses.

5.2.1 PIEDMONT DRAINAGE

The Piedmont drainage is the northernmost drainage in Delaware. The key wildlife habitats found in the Piedmont drainage are coastal plain upland forest, early successional habitat, floodplains, swamps, and other forested wetlands, freshwater tidal habitats (primarily marsh), coastal plain seasonal ponds, Piedmont Stream Valley wetlands, and non-tidal coastal plain streams, riverine aquatic, and SAV. The following exhibits outline the habitat loss and degradation scores for the predicted loss of wetlands from 2007 to 2022.

EXHIBIT 56. MAP OF HABITATS AND WETLAND LOSS WITHIN PIEDMONT DRAINAGE

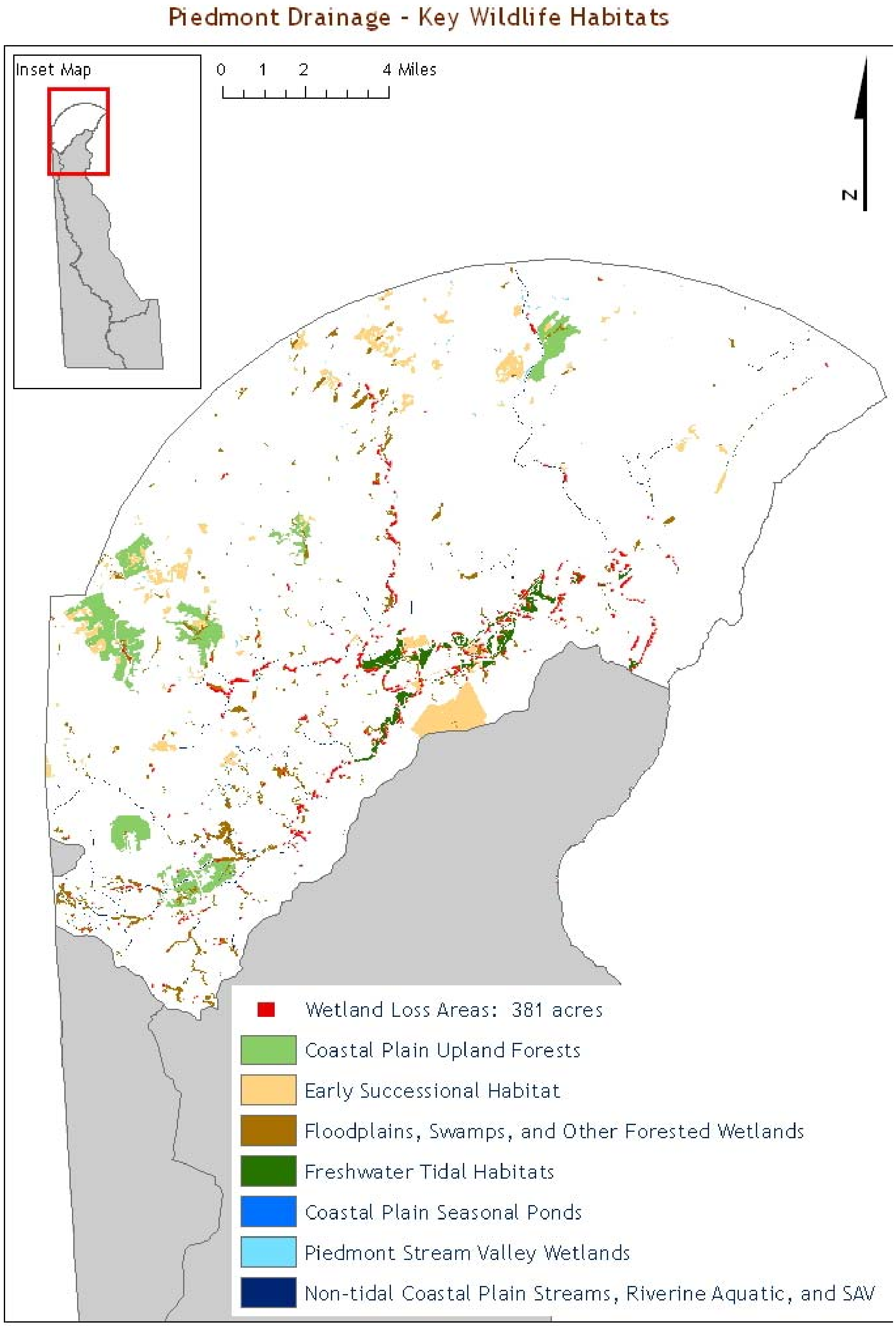


EXHIBIT 57. ESTIMATE OF HABITAT LOSS WITHIN PIEDMONT DRAINAGE

HABITAT	HABITAT 2007 (ACRES)	HABITAT 2022 (ACRES)	HABITAT LOSS (ACRES)	HABITAT LOSS (%)
Coastal plain upland forest	3131	3131	N/A[a]	0.00%
Early successional habitat	2817	2812	5	0.17%
Floodplains, swamps, and other forested wetlands	2142	2022	120	**5.58%**
Freshwater tidal habitats	1037	995	43	**4.14%**
Coastal plain seasonal ponds	39	38	1	2.27%
Piedmont Stream Valley wetlands	98	97	1	0.68%
Non-tidal streams, riverine aquatic, and SAV	363	363	N/A[a]	0.00%

[a] Coastal plain upland forest and non-tidal coastal plain streams, riverine aquatic, and SAV habitat types are not projected to experience habitat loss. This is because the projected habitat losses are all associated with wetland habitat types. In other words, the wetland losses forecast in this analysis equate to losses across various habitat types. Because coastal plain upland forests and non-tidal coastal plain streams, riverine aquatic, and SAV habitats are not wetland habitats, they do not experience habitat losses.

EXHIBIT 58. CHANGE IN HABITAT DEGRADATION WITHIN PIEDMONT DRAINAGE

HABITAT	ACRES WITH INCREASE IN DEGRADATION	SUM DEGRADATION SCORE 2007	SUM DEGRADATION SCORE 2022	INCREASE IN DEGRADATION FROM 2007 TO 2022
Coastal plain upland forest	178	4694	4715	0.4%
Early successional habitat	42	3766	3769	0.07%
Floodplains, swamps, and other forested wetlands	658	7342	7502	**2.18%**
Freshwater tidal habitats	658	3454	3744	**8.42%**
Coastal plain seasonal ponds	8	101	102	1.29%
Piedmont Stream Valley wetlands	17	554	559	0.85%
Non-tidal streams, riverine aquatic, and SAV	106	2453	2502	2.00%

Of the eight key wildlife habitats in the Piedmont drainage, two habitat types experience relatively significant decreases in habitat area as a result of predicted wetland losses: floodplains, swamps, and other forested wetlands (120 acres totaling 5.58 percent of the habitat), and freshwater tidal habitats (43 acres totaling 4.14 percent of the habitat. These habitats types are particularly affected by wetland loss as each is characterized in part by the inclusion of wetland areas.

The decrease in habitat extent, however, is not the only potential impact on the ability of these habitats to provide for species of concern. Because the wetlands in and around the habitats are lost to land uses that act as threats (i.e., development and agriculture), the remaining habitat in 2022 also experiences an increase in degradation (i.e., edge effects associated with the introduced threats). The greatest increase in degradation is to floodplains, swamps, and other forested wetlands (658 acres experience increased degradation, resulting in a 2.18 percent increase in habitat degradation overall). Increased degradation in 658 acres of freshwater tidal habitats results in an 8.42 percent increase in overall habitat degradation level.

Floodplains, swamps, and other forested wetland habitats are characterized by red maple, and are found on seasonally inundated floodplains.[61] The SGCN most likely to be affected by both habitat loss and degradation within the drainage are the American restart, warbling vireo, and barred owl (non-tidal floodplains and swamp habitat), as well as the American bittern, least bittern, and king rail (freshwater tidal marsh habitat). In addition, loss and degradation of non-tidal floodplains in the basin affects habitat for bog turtles, spotted turtles, and long-tailed salamanders.[62]

5.2.2 DELAWARE BAY DRAINAGE

The Delaware Bay drainage covers much of the eastern half of the state and drains into Delaware Bay. The habitats found within Delaware Bay drainage are primarily coastal, and include beach and dune habitat, coastal plain upland forest, coastal plain seasonal ponds, early successional habitat, freshwater tidal habitats, floodplains, swamps, and other forested wetlands, non-tidal coastal plain streams, riverine aquatic, and SAV, and tidal marsh. The following exhibits describe the habitat loss and degradation scores for the predicted loss of wetlands from 2007 to 2022.

[61] Information provided by Karen Bennett, Delaware Department of Natural Resources and Environmental Control, on May 1, 2011 and May 2, 2011. Of note, not all acres of a particular habitat type support all of the SGCN identified in the Appendix.

[62] *Ibid.*

EXHIBIT 59. MAP OF HABITATS AND WETLAND LOSS WITHIN DELAWARE BAY DRAINAGE

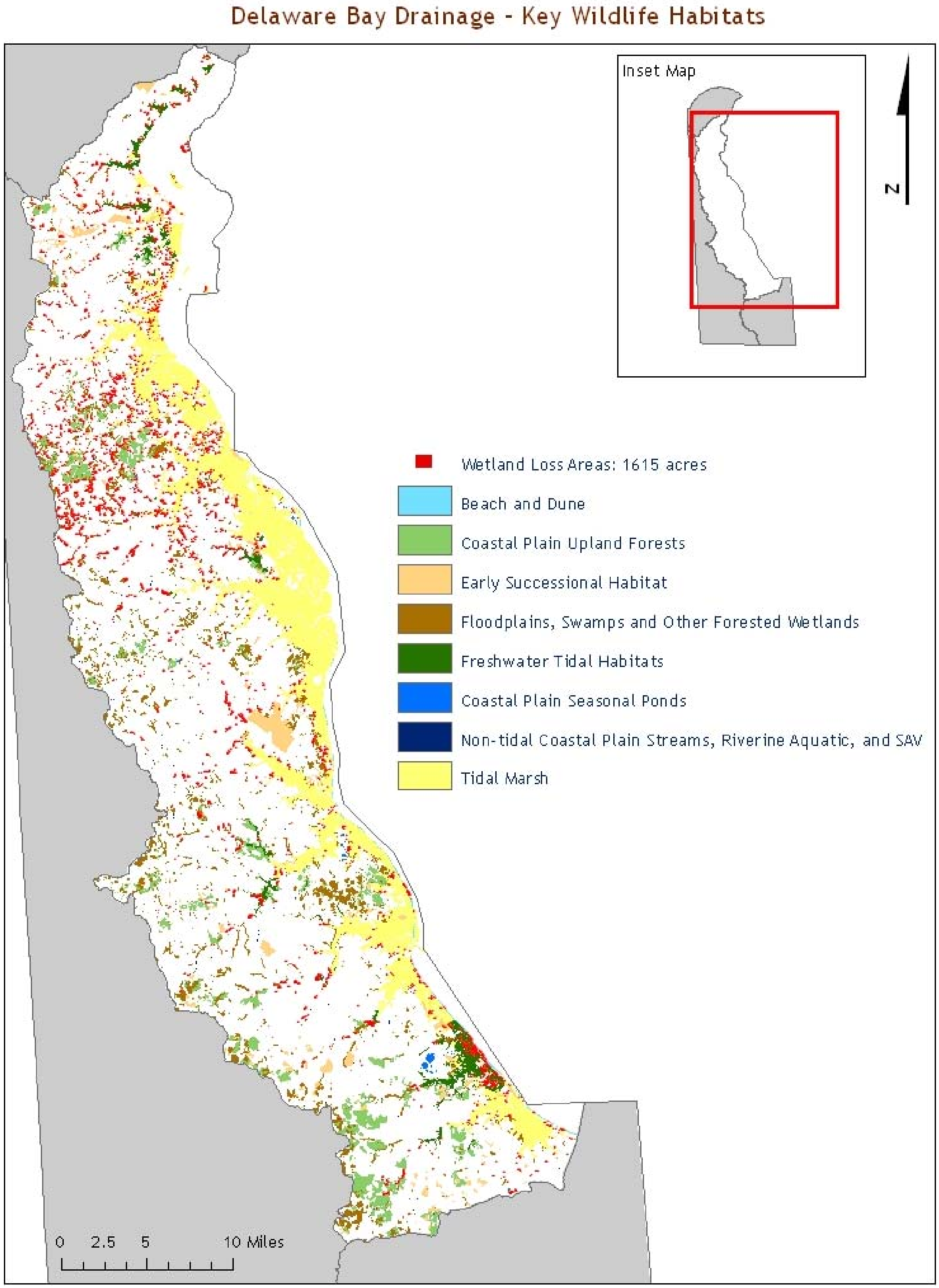


EXHIBIT 60. ESTIMATE OF HABITAT LOSS WITHIN DELAWARE BAY DRAINAGE

HABITAT	HABITAT 2007 (ACRES)	HABITAT 2022 (ACRES)	HABITAT LOSS (ACRES)	HABITAT LOSS (%)
Beach and dune	668	652	16	**2.46%**
Coastal plain upland forest	15478	15478	N/A[a]	0.00%
Early successional habitat	10147	10129	18	0.18%
Floodplain, swamp, and other forested wetlands	22357	21838	518	**2.32%**
Freshwater tidal habitats	7472	7306	165	**2.21%**
Coastal plain seasonal ponds	593	583	9	1.58%
Non-tidal coastal plain streams, riverine aquatic, and SAV	2106	2106	N/A[a]	0.00%
Tidal marsh	61680	61403	278	0.45%

[a] Coastal plain upland forest and non-tidal coastal plain streams, riverine aquatic, and SAV habitat types are not projected to experience habitat loss. This is because the projected habitat losses are all associated with wetland habitat types. In other words, the wetland losses forecast in this analysis equate to losses across various habitat types. Because coastal plain upland forests and non-tidal coastal plain streams, riverine aquatic, and SAV habitats are not wetland habitats, they do not experience habitat losses.

EXHIBIT 61. CHANGE IN HABITAT DEGRADATION WITHIN DELAWARE BAY DRAINAGE

HABITAT	ACRES WITH INCREASE IN DEGRADATION	SUM DEGRADATION SCORE 2007	SUM DEGRADATION SCORE 2022	INCREASE IN DEGRADATION FROM 2007 TO 2022
Beach and dune	228	746	749	0.49%
Coastal plain upland forest	1734	23708	23884	0.74%
Early successional habitat	234	10415	10426	0.10%
Floodplain, swamp, and other forested wetlands	3935	57397	58195	**1.39%**
Freshwater tidal habitats	1757	22348	22906	**2.49%**
Coastal plain seasonal ponds	85	1472	1486	0.97%
Non-tidal coastal plain streams, riverine aquatic, and SAV	394	11787	11892	0.89%
Tidal marsh	4617	52250	52927	**1.29%**

Within the Delaware Bay drainage, wetland losses lead to relatively significant losses in three habitat types. Floodplains, swamps, and other forested wetland habitats are projected to lose 518 acres of habitat (2.32 percent of these habitat types within the drainage). Tidal marsh habitats are projected to lose 278 acres (0.45 percent of habitat within the drainage). In addition, freshwater tidal habitat may experience a loss of 165 acres (2.21 percent of drainage within the habitat).

The same three habitat types are forecast to experience the greatest increases in degradation levels within the Delaware Bay drainage, as well. Approximately 3,935 acres of increased degradation in floodplains, swamps, and other forested wetland habitats results in an overall increase in habitat degradation of 1.39 percent. Increased degradation within 4,617 acres of tidal marsh habitat is expected to increase overall habitat degradation by 1.29 percent. Finally, increased degradation in 1,757 acres of freshwater tidal habitat results in a 2.49 percent increase in habitat degradation within the drainage.

Beach and dune habitat in Delaware Bay occupies a narrow strip of land along the Atlantic coast, and comprises beach, grassy dunes, overwashes and shrub-dominated back dunes.[63] The percent increase in degradation of the beach and dune habitats is relatively low at 0.5 percent. However, approximately 16 acres (2.5 percent) of this habitat type within the drainage would be lost. This may affect the viability of key SGCN occupying this habitat, including eight species of shorebirds.[64]

5.2.3 CHESAPEAKE BAY DRAINAGE

The Chesapeake Bay drainage is the furthest inland of the four main drainages in Delaware. Six key habitat types exist within the drainage, including coastal plain upland forest, coastal plain seasonal ponds, early successional habitat, freshwater tidal habitats, floodplains, swamps, and other forested wetlands, and non-tidal coastal plain streams, riverine aquatic, and SAV. The following exhibits outline the habitat loss and percent change in degradation associated with our wetland loss scenario in the Chesapeake Bay drainage.

[63] Ibid.

[64] Of note, not all acres of a particular habitat type support all of the SGCN identified in the Appendix.

EXHIBIT 62. MAP OF HABITATS AND WETLAND LOSS WITHIN CHESAPEAKE DRAINAGE

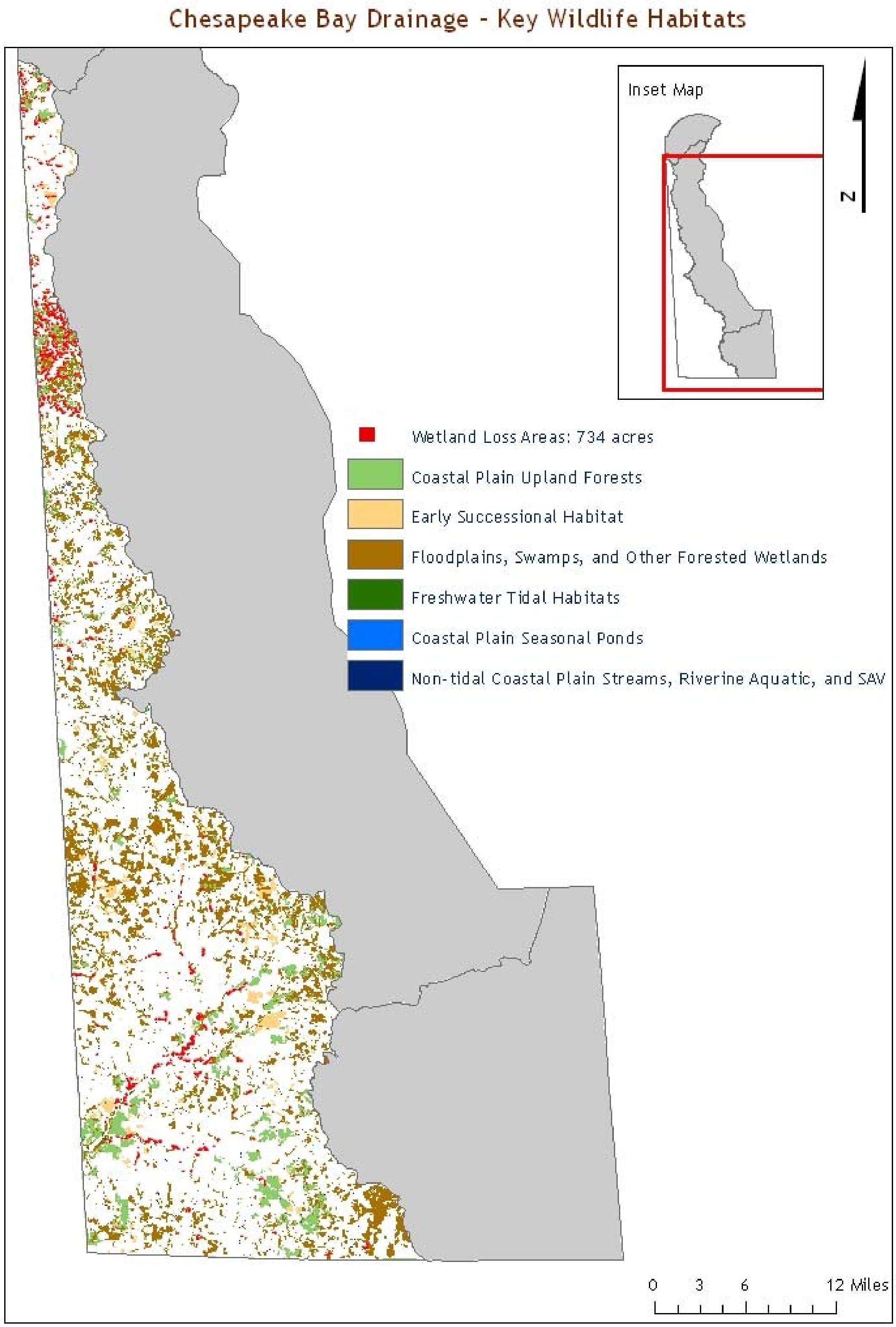


EXHIBIT 63. ESTIMATE OF HABITAT LOSS WITHIN CHESAPEAKE DRAINAGE

HABITAT	HABITAT 2007 (ACRES)	HABITAT 2022 (ACRES)	HABITAT LOSS (ACRES)	HABITAT LOSS (%)
Coastal plain upland forest	20539	20539	N/A[a]	0.00%
Early successional habitat	9757	9755	2	0.02%
Floodplains, swamps, and other forested wetlands	66492	66125	367	0.55%
Freshwater tidal habitats	361	348	13	**3.63%**
Coastal plain seasonal ponds	357	350	8	**2.12%**
Non-tidal coastal plain streams, riverine aquatic, and SAV	4854	4854	N/A[a]	0.00%

[a] Coastal plain upland forest and non-tidal coastal plain streams, riverine aquatic, and SAV habitat types are not projected to experience habitat loss. This is because the projected habitat losses are all associated with wetland habitat types. In other words, the wetland losses forecast in this analysis equate to losses across various habitat types. Because coastal plain upland forests and non-tidal coastal plain streams, riverine aquatic, and SAV habitats are not wetland habitats, they do not experience habitat losses.

EXHIBIT 64. CHANGE IN HABITAT DEGRADATION WITHIN CHESAPEAKE DRAINAGE

HABITAT	ACRES WITH INCREASE IN DEGRADATION	SUM DEGRADATION SCORE 2007	SUM DEGRADATION SCORE 2022	INCREASE IN DEGRADATION FROM 2007 TO 2022
Coastal plain upland forest	1551	25248	25403	0.61%
Early successional habitat	116	4212	4219	0.16%
Floodplains, swamps, and other forested wetlands	3692	123113	123925	0.66%
Freshwater tidal habitats	134	1452	1511	**4.10%**
Coastal plain seasonal ponds	133	636	668	**5.08%**
Non-tidal coastal plain streams, riverine aquatic, and SAV	302	27257	27388	0.48%

Key habitats losses within the Chesapeake Bay drainage occur within three habitat types. Floodplains, swamps, and other forested wetlands are projected to lose 367 acres (0.55 percent) of habitat within the drainage. While the 13 acre loss in freshwater tidal habitats and eight acre loss in coastal plain seasonal pond habitat may seem modest, these losses represent 3.63 percent and 2.12 percent of these habitat types, respectively.

These latter two habitat types also experience the greatest increase in degradation of greater than four percent. This is due to increased degradation in 134 acres of freshwater tidal habitats and 133 acres of coastal plain seasonal ponds. While the increased degradation may seem to apply to a relatively modest number of acres of these habitat types (134 and 133 acres), the overall effect on habitat degradation is significant due to relatively small size of existing habitat of these types within the drainage (361 and 357 acres respectively). All other habitat types experience an increase in habitat degradation of less than 0.7 percent within the drainage.

Coastal plain seasonal ponds, however, are forecast to experience the greatest increases in degradation within the Chesapeake Bay drainage. Coastal plain seasonal ponds are small depressional wetlands that act as vernal pools, only containing water in the winter and spring.[65] The habitat is largely unprotected (only 18 percent as of 2006), and is important habitat for breeding amphibians and insects (see Appendix C). The overall size of this habitat in the state (1,021 acres), and its dependency on maintained forest buffers and interconnected ponds, indicates that any decrease in extent and increase in degradation may have critical consequences on dependent SGCN.[66]

5.2.4 INLAND BAYS DRAINAGE

The Inland Bays drainage is characterized by a large inland body of water that drains to the Atlantic Ocean. The drainage is home to several tidal and upland habitats, including beach and dune habitat, coastal plain upland forest, coastal plain seasonal ponds, early successional habitat, freshwater tidal habitats, floodplains, swamps, and other forested wetlands, non-tidal coastal plain streams, riverine aquatic, and SAV, interdunal swales, and tidal marsh.

[65] Ibid.

[66] Of note, not all acres of a particular habitat type support all of the SGCN identified in the Appendix.

EXHIBIT 65. MAP OF HABITATS AND WETLAND LOSS WITHIN INLAND BAYS DRAINAGE

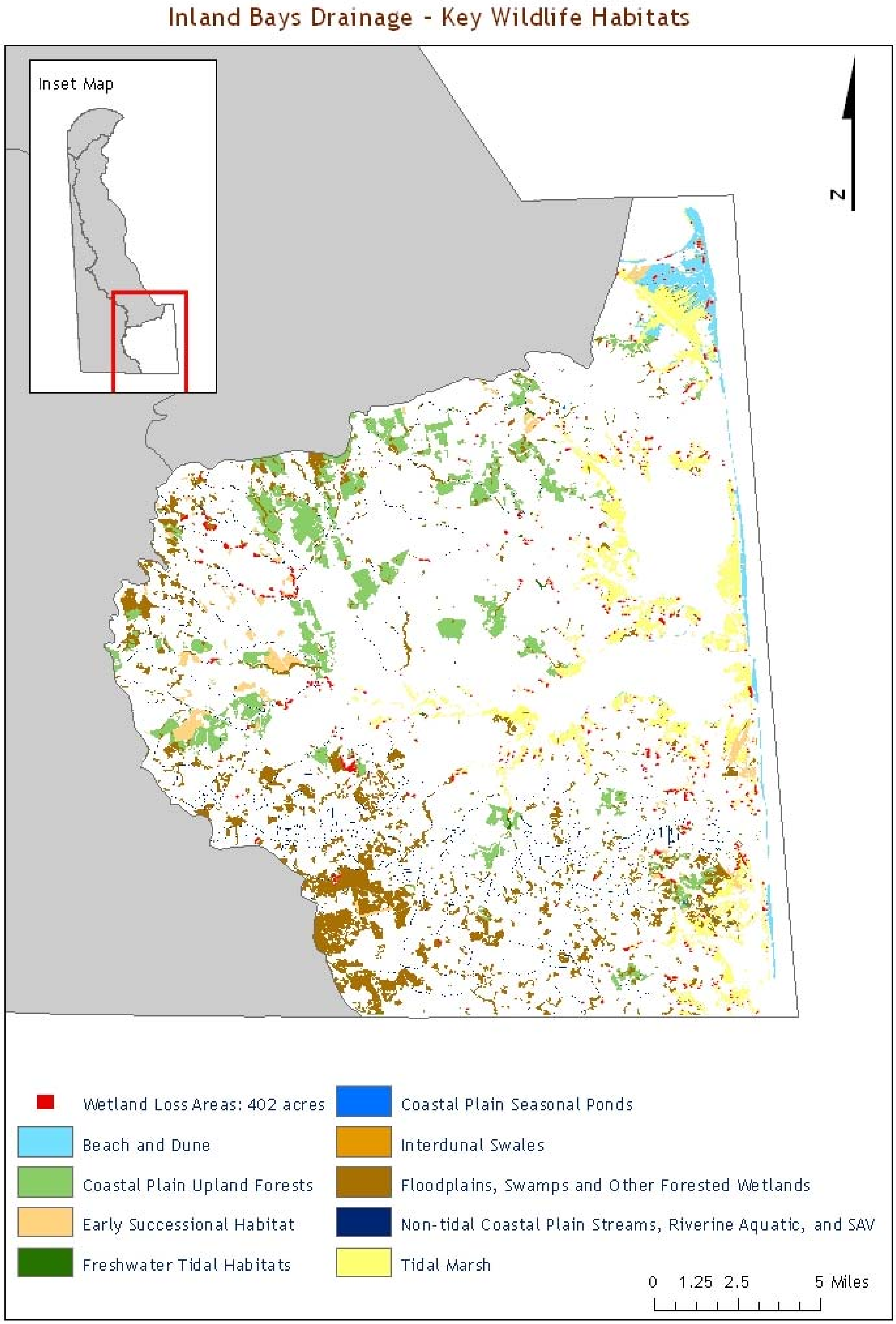


EXHIBIT 66. ESTIMATE OF HABITAT LOSS WITHIN INLAND BAYS DRAINAGE

HABITAT	HABITAT 2007 (ACRES)	HABITAT 2022 (ACRES)	HABITAT LOSS (ACRES)	HABITAT LOSS (%)
Beach and dune	2691	2668	23	0.85%
Coastal plain upland forest	10676	10676	N/A[a]	0.00%
Early successional habitat	2447	2445	2	0.09%
Floodplains, swamps, and other forested wetlands	13727	13593	134	0.98%
Freshwater tidal habitats	96	95	1	0.69%
Coastal plain seasonal ponds	32	32	0	0.00%
Interdunal swales	73	67	5	**7.34%**
Non-tidal coastal plain streams, riverine aquatic, and SAV	1591	1591	N/A[a]	0.00%
Tidal marsh	9560	9450	110	**1.15%**

[a] Coastal plain upland forest and non-tidal coastal plain streams, riverine aquatic, and SAV habitat types are not projected to experience habitat loss. This is because the projected habitat losses are all associated with wetland habitat types. In other words, the wetland losses forecast in this analysis equate to losses across various habitat types. Because coastal plain upland forests and non-tidal coastal plain streams, riverine aquatic, and SAV habitats are not wetland habitats, they do not experience habitat losses.

EXHIBIT 67. CHANGE IN HABITAT DEGRADATION WITHIN INLAND BAYS DRAINAGE

HABITAT	ACRES WITH INCREASE IN DEGRADATION	SUM DEGRADATION SCORE 2007	SUM DEGRADATION SCORE 2022	INCREASE IN DEGRADATION FROM 2007 TO 2022
Beach and dune	939	4342	4354	0.28%
Coastal plain upland forest	411	17431	17474	0.24%
Early successional habitat	20	990	992	0.14%
Floodplains, swamps, and other forested wetlands	407	25315	25386	0.28%
Freshwater tidal habitats	19	462	464	0.41%
Coastal plain seasonal ponds	3	62.8	63.2	0.59%
Interdunal swales	10	233	234	**0.63%**
Non-tidal coastal plain streams, riverine aquatic, and SAV	48	11824	11839	0.13%
Tidal marsh	2130	14679	15053	**2.55%**

In the Inland Bays drainage, three habitat types are projected to experience relatively significant habitat loss. Floodplains, swamps, and other forested wetlands habitat is forecast to lose 134 acres (0.98 percent) due to wetland losses. In addition, our analysis projects a 110 acre (1.15 percent) loss in tidal marsh habitat. Beach and dune habitat may also experience a 23 acre (0.85 percent) loss in habitat extent within the drainage. Of particular note, interdunal swales habitat is only found in the Inland Bays drainage and is present at low levels relative to other habitat types. As a result, while this habitat type is projected to lose only five acres, a 7.34 percent decrease in extent of habitat. Interdunal swales are found among dunes in the south eastern part of the state, and experience seasonal flooding. Only 73 acres of this habitat type exist within the state, and it supports two SGCN both insects, as described in Appendix C. The habitat is also home to more than 20 species of rare plants.[67]

On top of the habitat loss, one key habitat type, tidal marsh, is forecast to experience a 2.55 percent increase in degradation level within the drainage due to increased degradation on 2,130 acres of this habitat type.

5.3 ECONOMIC IMPLICATIONS

Conservation of wetland habitats in Delaware contributes to the protection of sensitive, threatened, endangered, and other species. Economists and ecologists have long debated the feasibility and practicality of valuing biodiversity in economic terms.[68] Clearly, diversity in plant and animal species is required for a functioning ecosystem. Key issues arise, however, from the difficulty in defining and measuring biodiversity for the purposes of valuation. The question of the level at which a decline in diversity affects the functioning of an ecosystem, and in what way, is a difficult one. This complicates the measurement of meaningful marginal economic values (i.e., the impacts of changes in the level of biodiversity associated with conservation management decisions).

Multiple categories of economic value are potentially relevant to biodiversity in Delaware, including:

- **Use value** – Relates to the direct or indirect use of species. This includes both consumptive use of species, such as hunting, and passive use, such as wildlife viewing.
- **Option value –** The preference for preserving species diversity for potential future use.[69]

[67] Ibid.

[68] For example: 1) Pearce, David and Dominic Moran, in association with the World Conservation Union. The Economic Value of Biodiversity. London: Earthscan Publications, Ltd. 1994; 2) Gowdy, John M."The Value of Biodiversity: Markets, Society, and Ecosystems." Land Economics 73(1) (1997): 25-41; 3) Simpson, David R. "Definitions of Biodiversity and Measures of Its Value." Resources for the Future: Discussion Paper 02-62. Washington, DC: Resources for the Future. November 2002; and 4) Ash, Neville and Martin Jenkins. "Biodiversity and Poverty Reduction: The Importance of Biodiversity for Ecosystem Services." Report of the United Nations Environment Programme World Conservation Monitoring Centre. May 2007.

[69] After some theoretical discourse option value (now referred to as an "option price") is recognized as an individual's value for a quantity or quality change when future supply or demand is uncertain, rather than a separate component of total economic value (e.g., see Freeman, 2003). We retain the terminology for expository purposes and note that it is a likely motivation for preferences for habitat preservation.

- **Bequest value –** The preference for preserving species and habitat as an environmental legacy for future generations.
- **Existence value –** Value derived from the knowledge of the species' or habitats' continued existence.[70]

While we do not monetize the value of biodiversity in this analysis, the following discussion provides information on some of these categories of value of wildlife in Delaware. Importantly, the values provided in this discussion are not losses in ecosystem service values associated with the habitats loss and degradation described in Section 5.2.

Any monetization of biodiversity changes would entail establishing multiple functional relationships that are beyond the scope of this report, including: 1) the biophysical relationship between level of habitat degradation or acres of habitat and species richness and/or abundance; and 2) the relationship between species richness and/or abundance and level or quality of the various economic activities (e.g., hunting, fishing, etc.). Thus, we note that while *any level* of habitat degradation is likely to manifest in negative economic consequences, valuation of such changes is subject to uncertainty sufficient to question the ultimate reliability of results. This economic information is therefore provided as context for the analysis and to demonstrate that the species and habitats within the state contribute positive economic value for citizens, visitors, and the state's economy.

Species and habitats in Delaware support economic activities by providing opportunity for recreational wildlife-viewing, hunting, and fishing, among other activities. Citizens and visitors to the state may therefore experience reduced quality of recreational activities due to degraded habitat conditions or declining species populations. In economic terms, the reduced value individuals hold for participating in recreational activities under degraded conditions is described as a "social welfare cost."

To the extent that wetland loss and habitat degradation reduce overall levels of wildlife-related recreation (i.e., the quality or quantity of recreational opportunities is reduced to a level such that some individuals no longer participate), businesses may suffer reduced revenues due to decreased spending (e.g., equipment and travel expenses) on wildlife-related activities. The resulting changes in regional income and employment are known as "regional economic impacts."

In 2006, 159,000 individuals participated in recreational fishing activities in the State of Delaware. These individuals contributed roughly $97 million dollars to the regional economy in 2006 through expenditures on equipment and fishing trip-related expenditures, such as food, lodging, and transportation. Approximately 38 percent of these expenditures were associated with visitors to Delaware, while the remainder was spent by state residents. While information is not available on the specific locations visited by anglers, approximately 73 percent participated in saltwater fishing and the remainder focused on freshwater habitats.[71]

---

[70] Pearce, David and Dominic Moran, in association with the World Conservation Union. The Economic Value of Biodiversity. London: Earthscan Publications, Ltd. 1994.

[71] U.S Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation: Delaware.

Another 30,000 individuals participated in recreational hunting in the same year, contributing approximately $41 million to the state's economy. These expenditures are attributed relatively equally to residents and visitors. About 73 percent of hunting trips were for big game hunting, such as deer. Another 15 percent of trips were for migratory bird hunts, including for waterfowl such as geese and ducks. Information is not available on the specific locations targeted by these hunters; however, approximately 63 percent hunted exclusively on private lands and 16 percent exclusively on public lands.[72]

Wildlife-watching also contributed measurably to the regional economy in 2006, with 285,000 participants spending $131 million in the state on equipment and trip-related expenditures. A significant majority, 81 percent, of the expenditures were attributable to residents of the state. This activity includes individuals that feed, observe, and photograph wildlife. Wildlife-watchers most frequently targeted wild bird species, including songbirds, water birds, and birds of prey.[73]

These economic activities and values are not exclusively associated with the habitat areas identified as potentially affected by wetland loss, but pertain to all wildlife-related recreation statewide. These values should therefore not be considered ecosystem value losses associated with our wetland loss scenario. However, as demonstrated in Section 5.2, the wetland losses forecast in our analysis affect the quality of multiple habitats, and associated biodiversity, across the state.

5.4 KEY UNCERTAINTIES

Exhibit 68 summarizes the key uncertainties of this analysis. These uncertainties are ranked in terms of their significance with respect to the results of this analysis presented in Section 5.2. As we do not monetize the changes in habitat degradation for the reasons described above, the uncertainties presented relate to the inherent variability in how specific habitat sites respond to land use threats.

[72] *Ibid.*

[73] *Ibid.*

EXHIBIT 68. KEY UNCERTAINTIES ASSOCIATED WITH THE WILDLIFE HABITAT ANALYSIS

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON RESULTS
We assume all habitats within a particular habitat type are equally sensitive to a given land use threat.	**Unknown.** May overestimate or underestimate effect on habitat degradation.	**Potentially major.** In assuming all habitat within a particular habitat type is equally sensitive to a given threat, we do not account for potential conservation efforts that may be undertaken at a particular habitat site to protect against or mitigate threats. In the case that conservation efforts are occurring, and are effective, we overstate the effect of our wetland losses on habitat quality at these sites. In addition, habitat that is already significantly degraded may be less resilient than other habitat areas to new threats. In this case, we may underestimate the effect of the wetland loss on habitat quality.
We assume the relative rankings of the sensitivity of each habitat type to various threats described in Exhibit 53.	**Unknown.** May overestimate or underestimate effect on habitat degradation.	**Potentially major.** The relative sensitivity of habitat to the various land use threats is a key input of the analysis. To the extent that these sensitivity estimates do not capture the relative sensitivity of habitat to the various threats, the results of this analysis may change significantly.
We assume the land use threats described in Exhibit 52 are additive in terms of impact on habitat quality.	May **underestimate** overall effect on habitat degradation.	**Potentially major.** It is possible that the combined effects of particular threats on habitat are multiplicative instead of additive. However, our analysis focuses on the relative impact of wetland losses on degradation. Therefore, while this assumption may significantly affect the overall levels of habitat degradation, it is unlikely to significantly change the relative distribution of incrementally degraded habitat.
We account only for land use threats to habitat for which spatial data are available to determine the presence of the threat.	May **underestimate** overall effect on habitat degradation.	**Probably minor.** Habitat threats, such as the spread of invasive species and hydrological alterations are not incorporated into our analysis. While these threats may have a significant impact on habitat quality, our analysis focuses on the incremental effect associated with wetland losses. We present the relative change in habitat quality associated with the wetland losses. Adding additional threats in the analysis would affect the absolute level of habitat quality but is not likely to significantly change the relative distribution of incrementally degraded habitat.

SOURCE OF UNCERTAINTY	DIRECTION OF POTENTIAL BIAS	LIKELY SIGNIFICANCE RELATIVE TO KEY UNCERTAINTIES ON RESULTS
We do not forecast the additional threat to habitat associated with utility, road, and other infrastructure that may accompany the conversion of wetlands to development.	May **underestimate** overall effect on habitat degradation.	**Probably minor.** While the additional threat of additional infrastructure may be an indirect result of the conversion of wetlands to development, one factor in forecasting where wetlands may be converted to development is proximity to existing infrastructure that would support the development. We therefore expect the additional threat to habitat associated with development-related infrastructure to have a relatively minor effect on the overall results of the analysis.
We assume sensitivity of habitat to a given threat decreases exponentially with distance from the threat.	**Unknown.** May overestimate or underestimate effect on habitat degradation.	**Probably minor.** The impact of some threats on habitat quality may decrease linearly with distance or in some other fashion. The results of this analysis, however, are less sensitive to this assumption that to the estimated relative sensitivity of habitats to the various threats.

REFERENCES

Abu-Zreig, M., Rudra, R.P., Lalonde, M.N., Whiteley, H.R., Kaushik, N.K. "Experimental investigation of runoff reduction and sediment removal by vegetated filter strips." Hydrological Processes 18 (2004): 2029-2037.

Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. United Nations Food and Agriculture Organization Irrigation and Drainage Paper 56. 1998.

Ash, Neville and Martin Jenkins. "Biodiversity and Poverty Reduction: The Importance of Biodiversity for Ecosystem Services." Report of the United Nations Environment Programme World Conservation Monitoring Centre. May 2007.

Bernal, Blanca. "Carbon Pools and Profiles in Wetland Soils: The Effect of Climate and Wetland Type." M.S. Thesis, Ohio State University. Advisors: William J. Mitsch, Rattan Lal, and Richard P. Dicl. 2008.

Bliss, N.B., Waltman, S.W., and West, L., 2009, Detailed mapping of soil organic carbon stocks in the United States using SSURGO [abs.], in Fall Meeting, San Francisco, CA, Dec. 14-18, 2009, Eos Transactions, Suppl., v. 90, no. 52: Washington, D.C., American Geophysical Union, p. B51F-0367.

Bockstael, N., A.M. Freeman, R. Kopp, P. Portney and V.K. Smith. "On Measuring Economic Values for Nature." Environmental Science and Technology 34 (8) (2000): 1384-1389.

Bolstad and Vose. "Forest and Pasture Carbon Pools and Soil Respiration in the Southern Appalachian Mountains." Forest Science 51(4) (2005): 372-383.

Bransby, D. I., S. B. McLaughlin, and D. J. Parrish. "A review of carbon and nitrogen balances inswitchgrass grown for energy." Biomass and Bioenergy 14 (1998):379-384.

Brater, E.F., and King, H.W. Handbook of Hydraulics for the Solution of Hydraulic Engineering Problems. New York: McGraw-Hill, 1976. (Brater and King, 1976).

Bridgham, Scott D., J. Patrick Megonigal, Jason K. Keller, Norman B. Bliss, and Carl Trettin. "The Carbon Balance of North American Wetlands." Wetlands. Volume 26 No. 4, December 2006. pp. 889-916.

Brody, Samuel D., Sammy Zaheran, Praveen Maghelal, Himanshu Grover, and Wesley E. Highfield. "The Rising Costs of Floods." Journal of the American Planning Association 73(3) (2007): 330-345.

Canadell, J.; R.B. Jackson; J.R. Ehleringer; H.A. Mooney; O.E. Sala; E.D. Schulze. "Maximum rooting depth of vegetation types at the global scale." Oceologia 108 (1996): 583 – 595.

Chesapeake Bay Program Scientific and Technical Advisory Committee (STAC).Quantifying the Role of Wetlands in Achieving Nutrient and Sediment Reductions in Chesapeake Bay. November 2008.

Chow, V.T., D.R. Maidment, and L.W. Mays, 1988, Applied Hydrology,. McGraw-Hill Book Company.

Cleary, Pendall, and Ewers. "Aboveground and Belowground Carbon Pools After Fire in Mountain Sagebrush Steppe." Rangeland Ecology & Management 63(2) (2010):187-196.

Correll, D.L., T.E. Jordan, D.E. Weller. "Nutrient Flux in a Landscape: Effects of Coastal Land Use and Terrestrial Community Mosaic on Nutrient Transport to Coastal Waters." Estuaries. 15 (1992): 431-442.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. O'Neill, J. Paruelo, R. Raskin, P. Sutton and M. van den Belt. "The Value of the World's Ecosystem Services and Natural Capital." Nature 387 (1997): 253-260.

Delaware Department of Natural Resources and Environmental Control, Division of Water Resources. Inland Bays Pollution Control Strategy. May 2008.

Delaware Division of Fish and Wildlife, Delaware Department of Natural Resources and Environmental Control. Delaware Wildife Action Plan: 2007-2017. September 2006.

Delaware Environmental Observing System (DEOS), Delaware Environmental Monitoring and Observing Network (DEMON). Data for 2008 and 2009 for precipitation and reference evapotranspiration. Made available by the University of Delaware: http://www.deos.udel.edu/.

Elsey-Quirk, Tracy, Denise M. Seliskar, Christopher K. Sommerfield, and John L. Gallagher. "Salt Marsh Carbon Pool Distribution in a Mid-Atlantic Lagoon, USA: Sea Level Rise Implications." Wetlands (2011) 31: 87-99.

FEMA National Flood Insurance Program. Flooding and Flood Risks: The Cost of Flooding. Accessed at http://www.floodsmart.gov/floodsmart/pages/flooding_flood_risks/the_cost_of_flooding.jsp.

Gedan, Keryn B., Matthew L. Kirwin, Eric Wolanski, Edward B. Barbier, and Brian R. Silliman. The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm. Climate Change: DOI 10.1007/s10584-010-0003-7. Published online December 14, 2010.

Georgia Environmental Protection Division. Total Maximum Daily Load Evaluation for Eight Stream Segments in the Tennessee River Basin for Sediment. Submitted to the USEPA. January 2004.

Gowdy, John M."The Value of Biodiversity: Markets, Society, and Ecosystems." Land Economics 73(1) (1997): 25-41.

Hansen, LeRoy and Marc Ribaudo. Economic Measures of Soil Conservation Benefits: Regional Values for Policy Assessment. U.S. Department of Agriculture, Economic Research Service Technical Bulletin 1922. September 2008.

Holmes, Thomas P. "The Offsite Impact of Soil Erosion on the Water Treatment Industry." Land Economics 64 (4) (1988).

Hook, P.B. "Wetlands and Aquatic Processes: Sediment Retention in Rangeland Riparian Buffer" Journal of Environmental Quality 32 (2003): 1130-1137.

Indiana Department of Environmental Management. Limberlost Creek Watershed Sediment and Nutrient TMDL Assessment. Appendix A. Prepared for the USEPA. 2007.

Institute for Public Administration, Water Resources Agency College of Human Services, Education and Public Policy, University of Delaware. 2008. Development of Hydrogeomorphic Modifiers to the Statewide Wetlands Mapping Project (SWMP) Dataset for Selected Watersheds in the Delaware Estuary, State of Delaware. Summary report for Department of Natural Resources and Environmental Control. 34pp.

Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme. IPCC Guidelines for National Greenhouse Gas Inventories. Hayama, Japan. 2006.

Johnston, Carol A. "Sediment and Nutrient Retention by Freshwater Wetlands: Effects on Surface Water Quality." Critical Reviews in Environmental Science and Technology Volume 21 (1991): 491-565.

Leathers, Daniel, J., Robert Scarborough, and David R. Legates. March 2010. A Data GAP Analysis and Inland Inundation Survey for the Delaware Coastline: Final Report and Recommendations. Submitted to the Delaware Department of Natural Resources and Environmental Control. Appendix 8: Inland Inundation Level Data Recorded During Major Coastal Flooding Events.

McGuckin, K. 2011. Methods Used to Create Datasets for the Delaware State Wetlands Update. Conservation Management Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA. Enhanced NWI wetland maps (ESRI Shapefilles) provided by DNREC to IEc in July 2010.

Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis. Island Press: Washington, DC.

Mitsch, William J. and James G. Gosselink. Wetlands. Fourth Edition. Hoboken, NJ: John Wiley and Sons, Inc., 2007.

Mitsch, William J., James G. Gosselink, Christopher J. Anderson, and Li Zhang. Wetland Ecosystems. Hoboken, NJ: John Wiley and Sons, Inc., 2009.

Montana Department of Environmental Quality. Upper Jefferson River Tributary Sediment TMDLs and Framework Water Quality Improvement Plan. Appendix D. September 2009.

Montes, S. Hydraulics of Open Channel Flow. Baltimore: American Society of Civil Engineers, 1998. (Montes, 1998).

The Natural Capital Project. InVEST 1.004 Beta User's Guide: Integrated Valuation of Ecosystem Services and Tradeoffs. Ed: Heather Tallis and Taylor Ricketts. 2009.

New Castle County Unified Development Code. Section 40.04.110: District and Bulk Standards.

New Jersey Department of Environmental Protection, Valuing New Jersey's Natural Capital: An Assessment of the Economic Value of the State's Natural Resources, April, 2007.

Oesterheld, M., J. Loreti, M. Semmartin, and J. Paruelo. "Grazing, fire, and climate effects on primary productivity of grasslands and savannas." Ecosystems of the World (1999): 287-306.

Ohio Environmental Protection Agency, Division of Surface Water. Total Maximum Daily Loads for the Salt Creek Watershed. Appendix C. 2009.

Paul, E.A.; S.J. Morris; J. Six; K. Paustian; and E.G. Gregorich. "Interpretation of Soil Carbon and Nitrogen Dynamics in Agricultural and Afforest Soils." Soil Science Society of America Journal 67 (2003):1620 - 1628.

Pearce, David and Dominic Moran, in association with the World Conservation Union. The Economic Value of Biodiversity. London: Earthscan Publications, Ltd. 1994.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C, coordinators. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). United States Department of Agriculture, Agriculture Handbook No. 703. 1997.

Risser, P., E. Birney, H. Blocker, S. May, W. Parton, and J. Wiens. The True Prairie Ecosystem. New York: Hutchinson Ross Pub. Co. distributed by: Academic Press, Stroudsburg, Pa., 1981.

Saleh, D.K., Kratzer, C.R., Green, C.H., and Evans, D.G., 2009, Using the Soil and Water Assessment Tool (SWAT) to simulate runoff in Mustang Creek Basin, California: U.S. Geological Survey Scientific Investigations Report 2009–5031.

Sanborn Map Company, Inc. 2007 Delaware Land Use and Land Cover. 1st Edition. State of Delaware, Office of Management and Budget, Delaware Geographic Data Committee. 2007. GIS Shapefile.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. "Filter Strip Performance and Processes for Different Vegetation, Widths, and Contaminants." Journal of Environmental Quality 28 (1999): 1479-1489.

Schoonover, Jon E., Karl W. J. Williard, James J. Zaczekjean C. Mangun, and Andrew D. Carver. "Agricultural Sediment Reductions by Giant Cane and Forest Riparian Buffers." Water, Air and Soil Pollution 169 (2006): 303-315.

Simpson, David R. "Definitions of Biodiversity and Measures of Its Value." Resources for the Future: Discussion Paper 02-62. Washington, DC: Resources for the Future. November 2002.

Simpson, Thomas and Sarah Weamert. Developing Nitrgoen, Phosphorus and Sediment Reduction Efficiencies for Tributary Strategy Practices. BMP Assessment: Final Report. Report of the University of Maryland, Mid-Atlantic Water Program. March 2009.

Smith, J. E., L. S. Heath, K. E. Skog, and R. A. Birdsey. Methods for calculating forest ecosystem and forest types of the United States. United States Dept. of Agriculture, Forest Service, Northeastern Research Station. General Technical Report NE-343. 2006.

Soil Conservation Service, 1986. Urban Hydrology for Small Watersheds. Technical Release 55, Washington, D.C. (SCS, 1986).

State of Delaware National Flood Insurance Program Paid Claims (excel spreadsheet format). Provided to IEc by Micheal Powell, Flood Mitigation Program, DNREC via email on October 11, 2010.

Tiner, R.W., H.C. Bergquist, J.Q. Swords, and B.J. McClain. 2001. Watershed-based Wetland Characterization for Delaware's Nanticoke River Watershed: A Preliminary Assessment Report. U.S. Fish & Wildlife Service, National Wetlands Inventory (NWI) Program, Northeast Region, Hadley, MA. Prepared for the Delaware Department of Natural Resources and Environmental Control, Division of Soil and Water Conservation, Dover, DE. NWI technical report. 89 pp.

Tiner, R.W. Correlating Enhanced National Wetlands Inventory Data with Wetland Functions for Watershed Assessments: A Rationale for Northeastern U.S. Wetlands. U.S. Fish and Wildlife Service, National Wetlands Inventory Program, Region 5, Hadley, MA. 2003. 26 pp.

Tiner, R.W. "Background on LLWW and Preliminary Wetland Functional Assessment." Memorandum for the Association for State Wetland Managers (ASWM). December 2008.

Toll, Richard S.J. "The Economic Effects of Climate Change." Journal of Economic Perspectives 23:2 (2009): 29-51.

U.S. Dept. of Agriculture. Soil Conservation Service. 1972. National engineering handbook, Section 4, hydrology. Chapters 7, 8, 9, and 10. U.S. Govt. Print. Off. Washington, DC.

U.S. Department of Agriculture, Forest Service. Forest Inventory Data Online. "Aboveground Carbon Storage of Forests in Delaware." "Total Area of Forests in Delaware." Accessed September 22, 2010 at http://fiatools.fs.fed.us/fido/index.html.

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Soil Survey Geographic Database (SSURGO). Data for soil depth and plant available water content. Made available by the NRCS at http://soils.usda.gov/survey/geography/ssurgo/.

U.S Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation: Delaware.

U.S. Environmental Protection Agency. November 2009. Development Document for Final Effluent Guidelines and Standards for the Construction and Development Category. Table 3-3, "Rainfall Summary Data for Indicatory Cities."

U.S. Environmental Protection Agency Science Advisory Board, Committee on Valuing the Protection of Ecological Systems and Services. Valuing the Protection of Ecological Systems and Services: A Report of the EPA Science Advisory Board. May 2009. EPA-SAB-09-012.

U.S. Geological Survey (USGS) National Elevation Data, Delaware 1-Arc Second, Series Issue 0.1. Sioux Falls, SD: U.S. Geological Survey, 2002 – 2005.

Van Dikj, P.M., F.J.P.M. Kwaad, M. Klapwijk. "Retention of Water and Sediment by Grass Strips." Hydrological Processes 10 (1996): 1069-1080.

Wamsley, T.V., et al.. The Potential of Wetlands in Reducing Storm Surge. Ocean Engineering 37 (1) (2010): 59-68.

Young, R.A., T. Huntrods, and W. Anderson. “Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff.” Journal of Environmental Quality 9 (1980): 483-487.

Zan, C., J. Fyles, P. Girouard, and R. Samson. “Carbon sequestration in perennial bioenergy, annual cornand uncultivated systems in southern Quebec.” Agriculture, Ecosystems and Environment 86 (2001):135-144.

Zhang, L., W.R. Dawes, and G.R. Walker. “Response of mean annual evapotranspiration to vegetation changes at catchment scale.” Water Resources Research 37 (2001): 701-708.