# Optimization of Salt Marsh Management at the Bombay Hook National Wildlife Refuge, Delaware, Through Use of Structured Decision Making

Open-File Report 2018–1160

U.S. Department of the Interior
U.S. Geological Survey

**Cover.** Photograph showing a salt marsh at the Bombay Hook National Wildlife Refuge in Delaware; photograph courtesy of Tim Williams, used with permission by the U.S. Fish and Wildlife Service.

# Optimization of Salt Marsh Management at the Bombay Hook National Wildlife Refuge, Delaware, Through Use of Structured Decision Making

By Hilary A. Neckles, James E. Lyons, Jessica L. Nagel, Susan C. Adamowicz, Toni Mikula, Susan T. Guiteras, and Laura R. Mitchell

Prepared in cooperation with the U.S. Fish and Wildlife Service

Open-File Report 2018–1160

**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
RYAN K. ZINKE, Secretary

**U.S. Geological Survey**
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2018

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Neckles, H.A., Lyons, J.E., Nagel, J.L., Adamowicz, S.C., Mikula, T., Guiteras, S.T., and Mitchell, L.R., 2018, Optimization of salt marsh management at the Bombay Hook National Wildlife Refuge, Delaware, through use of structured decision making: U.S. Geological Survey Open-File Report 2018–1160, 18 p., https://doi.org/10.3133/ofr20181160.

ISSN 2331-1258 (online)

# Acknowledgments

Virginia Rettig, Rich Albers, Paul Castelli, and Shane Daley of U.S. Fish and Wildlife Service (FWS) provided exceptional hospitality for the 2016 structured decision-making workshop at the Edwin B. Forsythe National Wildlife Refuge, New Jersey. Glenn Guntenspergen, landscape ecologist with U.S. Geological Survey (USGS), and Greg Shriver, avian ecologist with University of Delaware, generously contributed their time and expertise during the workshop; their history developing metrics to assess salt marsh integrity and their knowledge of salt marsh ecosystem dynamics were extremely helpful in applying the structured decision-making framework to the Bombay Hook National Wildlife Refuge in Delaware. Nathan Bush of the FWS generated the mapping data used in this report, and Jackie Olson of the USGS expertly prepared the maps. Technical reviews by Rachel Katz of the FWS and Bill Thompson of National Park Service greatly improved the quality of this report. At the time of publication, data supporting this study have not been published by the FWS.

# Contents



## Figures



## Tables

## Conversion Factors

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |

## Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

## Abbreviations

| | |
|---|---|
| FWS | U.S. Fish and Wildlife Service |
| NWR | National Wildlife Refuge |
| NWRS | National Wildlife Refuge System |
| ppt | part per thousand |
| SMU | salt marsh unit |
| USGS | U.S. Geological Survey |

# Optimization of Salt Marsh Management at the Bombay Hook National Wildlife Refuge, Delaware, Through Use of Structured Decision Making

By Hilary A. Neckles,[1] James E. Lyons,[1] Jessica L. Nagel,[1] Susan C. Adamowicz,[2] Toni Mikula,[2] Susan T. Guiteras,[2] and Laura R. Mitchell[2]

## Abstract

Structured decision making is a systematic, transparent process for improving the quality of complex decisions by identifying measurable management objectives and feasible management actions; predicting the potential consequences of management actions relative to the stated objectives; and selecting a course of action that maximizes the total benefit achieved and balances tradeoffs among objectives. The U.S. Geological Survey, in cooperation with the U.S. Fish and Wildlife Service, applied an existing, regional framework for structured decision making to develop a prototype tool for optimizing salt marsh management decisions at the Bombay Hook National Wildlife Refuge in Delaware. Refuge biologists, refuge managers, and research scientists identified multiple potential management actions to improve the ecological integrity of eight salt marsh units within the refuge and estimated the outcomes of each action in terms of performance metrics associated with each management objective. Value functions previously developed at the regional level were used to transform metric scores to a common utility scale, and utilities were summed to produce a single score representing the total management benefit that would be accrued from each potential management action. Constrained optimization was used to identify the set of management actions, one per salt marsh unit, that would maximize total management benefits at different cost constraints at the refuge scale. Results indicated that for the objectives and actions considered here, total management benefits would increase consistently up to approximately $300,000, but that further expenditures would yield diminishing return on investment. Management actions selected within optimal portfolios at total costs less than $300,000 included hydrologic restoration, recontouring adjacent uplands to facilitate marsh migration, and burning the marsh. The prototype presented here provides a framework for decision making at the Bombay Hook National Wildlife Refuge that can be updated as new data and information become available.

## Introduction

The National Wildlife Refuge System (NWRS) protects extensive salt marsh acreage in the northeastern United States. Much of this habitat has been degraded by a succession of human activities since the time of European settlement (Gedan and others, 2009), and accelerated rates of sea-level rise exacerbate these effects (Gedan and others, 2011; Kirwan and Megonigal, 2013). Therefore, strategies to restore and enhance the ecological integrity of National Wildlife Refuge (NWR) salt marshes are regularly considered. Management may include such activities as reestablishing natural hydrology, augmenting or excavating sediments to restore marsh elevation, controlling invasive species, planting native vegetation, minimizing shoreline erosion, and remediating contaminant problems. Uncertainty stemming from incomplete knowledge of system status and imperfect understanding of ecosystem dynamics commonly hinders management predictions and consequent selection of the most effective management options. Consequently, tools for identifying appropriate assessment variables and evaluating tradeoffs among management objectives are valuable to inform marsh management decisions.

Structured decision making is a systematic approach to improving the quality of complex decisions that integrates assessment metrics into the decision process (Gregory and Keeney, 2002). This approach involves identifying measurable management objectives and potential management actions, predicting management outcomes, and evaluating tradeoffs to choose a preferred alternative. From 2008 to 2012, the U.S. Geological Survey (USGS) and U.S. Fish and Wildlife Service (FWS) used structured decision making to develop a framework for optimizing management decisions for NWR salt marshes in the FWS Northeast Region (that is, salt

[1]U.S. Geological Survey.

[2]U.S. Fish and Wildlife Service.

marshes in the coastal region from Maine through Virginia). The structured decision-making steps were applied through successive "rapid prototyping" workshops, an iterative process in which relatively short periods of time are invested to continually improve the decision structure (Blomquist and others, 2010; Garrard and others, 2017). The decision framework includes regional management objectives addressing critical components of salt marsh ecosystems and associated performance metrics for determining whether objectives are achieved (Neckles and others, 2015). The regional objectives structure served as the foundation for a consistent protocol for monitoring salt marsh integrity at these northeastern coastal refuges, in which the monitoring variables are linked explicitly to management goals (Neckles and others, 2013). From 2012 to 2016, this protocol was used to conduct a baseline assessment of salt marsh integrity at all 17 refuges or refuge complexes in the FWS Northeast Region with salt marsh habitat (fig. 1).

The Bombay Hook National Wildlife Refuge, in coastal Delaware, protects one of the largest remaining tracts of salt marsh in the mid-Atlantic region (FWS, 2014). The refuge's salt marsh, considered its most valuable habitat (FWS, 2013), has been altered substantially by human activities from colonial to recent times. Historical alterations include

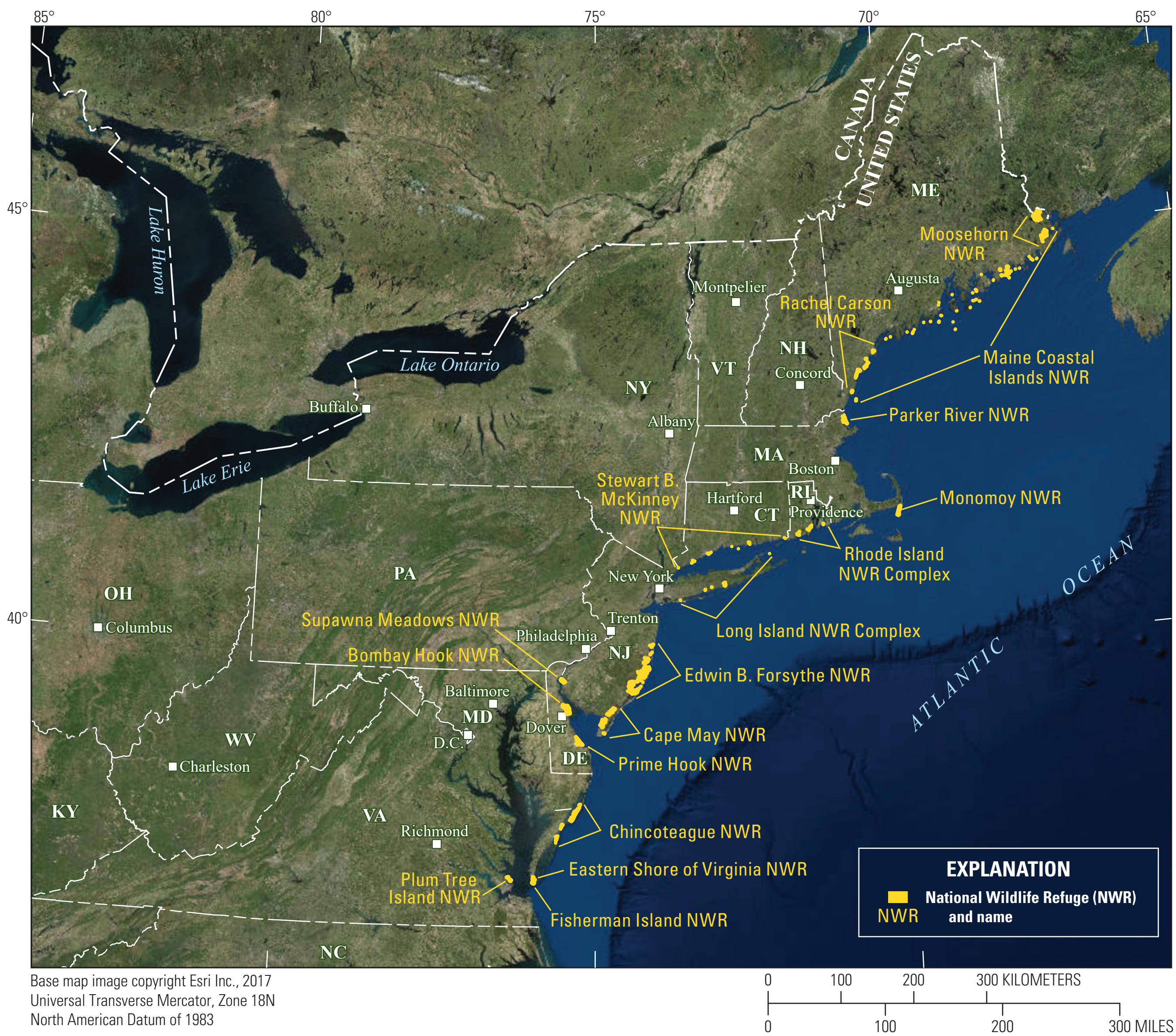



**Figure 1.** National Wildlife Refuges and National Wildlife Refuge Complexes of the U.S. Fish and Wildlife Service where salt marsh integrity was assessed from 2012 to 2016 using the regional monitoring protocol.

construction of canals, extensive ditching, and other changes to natural hydrology (FWS, 2016). Some areas of the marsh have been invaded by *Phragmites australis* (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017), and marsh edges bordering Delaware Bay are subject to erosion (FWS, 2016). Primary management concerns are loss of the marsh platform through shoreface erosion coupled with submergence resulting from rising sea level (McDowell, 2017). Refuge managers and biologists are actively engaged in identifying opportunities for possible salt marsh restoration (FWS, 2013). Therefore, in this study, the regional structured decision-making framework was used to help prioritize salt marsh management options for the refuge.

## Purpose and Scope

This report describes the application of the regional structured decision-making framework (Neckles and others, 2015) to the Bombay Hook National Wildlife Refuge. The regional framework was parameterized to local conditions through rapid prototyping, producing a decision model for the refuge that can be updated as new information becomes available. Included are a suite of potential management actions to achieve objectives in eight salt marsh units at the refuge, approximate cost estimates for implementing each potential action, predictions for the outcome of each management action relative to individual management objectives, and results of constrained optimization to maximize management benefits subject to cost constraints. This decision structure can be used to understand how specific actions may contribute to achieving management objectives and identify an optimum combination of actions, or "management portfolio," to maximize management benefits at the refuge scale for a range of potential budgets. The prototype presented here provides a framework for continually improving the quality of complex management decisions at the Bombay Hook National Wildlife Refuge.

## Description of Study Area

The Bombay Hook National Wildlife Refuge is a tidal marsh-dominated system along the Delaware Bay in Kent County, Delaware (fig. 2). About 5,000 hectares of salt marsh is divided into eight salt marsh management units: Leatherberry (SMU–1), Bombay Hook Island North (SMU–2), Georges Island (SMU–3), Bombay Hook Island South (SMU–4), Kent Island (SMU–5), Kelly Island (SMU–6), Steamboat (SMU–7), and Air Force (SMU–8). The managed marsh area is bordered by Delaware Bay to the east and primarily by adjoining marsh land to the south, west, and north, leading to mostly natural surrounding landscapes; however, George's Island (SMU–3) and Steamboat (SMU–7) do have small areas of agricultural land nearby. None of the salt marsh units have tidal restrictions, but two (Steamboat [SMU–7] and Air Force [SMU–8]) are heavily ditched. From 2012 to 2014, average surface-water salinities in summer ranged from 13 parts per thousand (ppt) at Bombay Hook Island North (SMU–2) to 17 ppt at Bombay Hook Island South (SMU–4) and George's Island (SMU–3; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017).

# Regional Structured Decision-Making Framework

A regional framework for assessing and managing salt marsh integrity at northeastern NWRs was developed through collaborative efforts of FWS regional and refuge managers and biologists, salt marsh research scientists, and structured decision-making experts. This process followed the discrete steps outlined by Hammond and others (1999) and Gregory and Keeney (2002):

1. Clarify the temporal and spatial scope of the management decision.
2. Define objectives and performance measures to evaluate whether objectives are achieved.
3. Develop alternative management actions for achieving objectives.
4. Estimate the consequences or likely outcomes of management actions in terms of the performance measures.
5. Evaluate the tradeoffs inherent in potential alternatives and select the optimum alternatives to maximize management benefits.

This sequence of steps was applied through successive workshops to refine the decision structure and incorporate newly available information. Initial development of the structured decision-making framework occurred during a week-long workshop in 2008 to define the decision problem, specify management objectives, and explore strategies available to restore and enhance salt marsh integrity (Neckles and others, 2013). During 2008 and 2009, workshop results were used to guide field tests of salt marsh monitoring variables (Neckles and others, 2013). Subsequently, in 2012, data and insights gained from these field tests were used in a two-part workshop to refine management objectives and develop the means for evaluating management outcomes (Neckles and others, 2015).

From the outset, FWS goals included development of an approach for consistent assessment of salt marsh integrity across all northeastern NWRs (fig. 1). Within this regional context, staff at a given refuge must periodically determine the best approaches for managing salt marshes to maximize habitat value within financial and other constraints. The salt marsh decision problem was thus defined as applying to individual NWRs over a 5-year planning horizon. The objectives for complex decisions can be organized into a hierarchy to help clarify what is most important to decision makers (Gregory


**Figure 2.** Salt marsh units at the Bombay Hook National Wildlife Refuge in Delaware.

and others, 2012). The hierarchy of objectives for salt marsh management decisions (table 1) was based explicitly on the conservation mission of the NWRS, which is upheld through management to "ensure that the biological integrity, diversity, and environmental health of the System are maintained for the benefit of present and future generations of Americans," as mandated in the National Wildlife Refuge System Improvement Act of 1997 (16 U.S.C. 668dd note). Two fundamental objectives, or the overall goals for salt marsh management decisions, were drawn from this policy to maximize (1) biological integrity and diversity and (2) environmental health of salt marsh ecosystems. Participants in the prototyping workshops deconstructed these overall goals into low-level objectives relating to salt marsh structure and function and identified performance metrics to evaluate whether objectives are achieved (table 1). In addition, performance metrics were weighted to reflect the relative importance of each objective (Neckles and others, 2015).

The hierarchy of objectives for salt marsh management (table 1) provides the foundation for identifying possible management actions at individual NWRs and predicting management outcomes. Workshop participants developed preliminary influence diagrams, or conceptual models relating management actions to responses by each performance metric (Conroy and Peterson, 2013), to guide this process. To allow metric responses to be aggregated into a single, overall performance score, participants also defined value functions relating salt marsh integrity metric scores to perceived management benefit on a common, unitless "utility" scale (Keeney and Raiffa, 1993). Stakeholder elicitation was used to determine the form of each value function relating the original metric scale to the utility scale, ranging from 0, representing the lowest management benefit, to 1, representing the highest benefit (appendix 1). Neckles and others (2015) described development of the structured decision-making framework and a case-study application to Prime Hook National Wildlife Refuge, Delaware, in detail.

**Table 1.** Objectives hierarchy for salt marsh management decision problems.

[Two fundamental objectives (overall goals of the decision problem) draw directly from National Wildlife Refuge System policy to maintain, restore, and enhance biological integrity, diversity, and environmental health within the refuge. These objectives are broken down into low-level objectives focused on specific aspects of marsh structure and function. Values in parentheses are weights assigned to objectives, reflecting their relative importance. Weights on any branch of the hierarchy sum to 1. The weight for each metric is the product of the weights from each level of the hierarchy leading to that metric. NA, not applicable]

| Objectives | Performance metrics | Unit of measurement |
|---|---|---|
| | Maximize biological integrity and diversity[1] (0.5) | |
| Maximize cover of native vegetation (0.24) | Cover of native vegetation | Percent |
| Maximize abundance and diversity of native nekton (0.18): | NA | NA |
| Maximize nekton abundance (0.50) | Native nekton density | Number per square meter |
| Maximize nekton diversity (0.50) | Native nekton species richness | Number of native species |
| Maintain sustainable populations of obligate salt marsh breeding birds (0.20) | Abundance of four species of tidal marsh obligate birds (clapper rail; willet; saltmarsh sparrow; seaside sparrow) | Number per salt marsh unit from call-broadcast surveys, summed across all sampling points in unit |
| Maximize use by nonbreeding wetland birds (0.20) | Abundance of American black duck as indicator species | Relative abundance for refuge during wintering waterfowl season (low, medium, high)[2] |
| Maintain trophic structure (0.18) | Density of spiders as indicator taxon | Number per square meter |
| | Maximize environmental health[1] (0.5) | |
| Maintain natural hydrology (0.44): | NA | NA |
| Maintain natural flooding regime (0.50) | Percent of time marsh surface is flooded relative to ideal reference system | Absolute deviation from reference in percentage points |
| Maintain natural salinity (0.50) | Surface-water salinity relative to ideal reference system | Absolute deviation from reference in parts per thousand |
| Maintain the extent of the marsh platform (0.44) | Change in marsh surface elevation relative to sea-level rise | 0=change in elevation is less than amount of sea-level rise; 1=change in elevation greater than or equal to sea-level rise |
| Minimize use of herbicides (0.12) | Rate of application | 0=no herbicide applied; 1=herbicide applied |

[1]Fundamental objectives of salt marsh management decisions.

[2]Relative abundance based on local knowledge.

# Application to the Bombay Hook National Wildlife Refuge

In November 2016, FWS regional biologists, biologists and managers from six northeastern NWR administrative units, and USGS and University of Delaware research scientists (table 2), participated in a 1.5-day rapid-prototyping workshop to apply the regional structured decision-making framework to the Chincoteague, Bombay Hook, Cape May, Supawna Meadows, and Forsythe National Wildlife Refuges and the Rhode Island National Wildlife Refuge Complex. Participants worked within refuge-specific small groups to focus on management issues at individual refuges. Plenary discussions of common patterns of salt marsh degradation, potential management strategies, and mechanisms of ecosystem response offered additional insights to enhance refuge-specific discussions.

**Table 2.** Participants in workshop convened at the Edwin B. Forsythe National Wildlife Refuge, New Jersey, to apply a regional framework for optimizing salt marsh management decisions to five National Wildlife Refuges in November 2016.

[FWS, U.S. Fish and Wildlife Service; NWR, National Wildlife Refuge; USGS, U.S. Geological Survey]

| Affiliation | Participant |
|---|---|
| FWS NWR specialists | |
| Bombay Hook NWR | Susan Guiteras |
| Cape May NWR and Supawna Meadows NWR | Brian Braudis |
| Cape May NWR and Supawna Meadows NWR | Heidi Hanlon |
| Cape May NWR and Supawna Meadows NWR | Victor Nage |
| Cape May NWR and Supawna Meadows NWR | Jack Szczepanski |
| Chincoteague NWR | Kevin Holcomb |
| Chincoteague NWR | Jennifer Miller |
| Edwin B. Forsythe NWR | Paul Castelli |
| Edwin B. Forsythe NWR | Virginia Rettig |
| Rhode Island NWR Complex | Nick Ernst |
| Rhode Island NWR Complex | Charlie Vandemoer |
| FWS regional experts | |
| Northeast Regional Office | Laura Mitchell |
| Rachel Carson NWR | Susan Adamowicz |
| Rachel Carson NWR | Toni Mikula |
| Research scientists | |
| University of Delaware | W. Gregory Shriver |
| USGS Patuxent Wildlife Research Center | Glenn Guntenspergen |
| USGS Patuxent Wildlife Research Center | James Lyons |
| USGS Patuxent Wildlife Research Center | Hilary Neckles |

Participants identified a range of possible management actions for achieving objectives within each salt marsh management unit at the Bombay Hook National Wildlife Refuge and estimated the total cost of implementation over 5 years. Potential actions to enhance salt marsh integrity ranged from focused efforts to restore hydrologic connections to larger scale projects to alter marsh elevation or vegetation succession (table 3). Participants predicted the outcomes of each management action 5 years after implementation in terms of salt marsh integrity performance metrics. For most metrics, baseline conditions within each unit measured during the 2012–16 salt marsh integrity assessment (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017) were used to predict the outcomes of a “no-action” alternative. However, for three metrics lacking assessment data (abundance of American black ducks, density of spiders, and change in marsh surface elevation relative to sea-level rise), baseline conditions were estimated by using expert judgement. Regional influence diagrams relating management strategies to outcomes aided in predicting consequences of management actions. Although the influence diagrams incorporated the potential effects of stochastic processes, including weather, sea-level rise, herbivory, contaminant inputs, and disease, on management outcomes, no attempt was made to quantify these sources of uncertainty during rapid prototyping. Management predictions also incorporated considerable uncertainty surrounding the complex interactions among controlling factors and salt marsh ecosystem response.

Following the workshop, the existing regional value functions (appendix 1) were applied to convert salt marsh integrity metric scores (workshop output in table 3) to weighted utilities (table 4), which could be equated to perceived management benefit relative to each salt marsh integrity performance metric. Weighted utilities were then summed across all salt marsh integrity metrics for each action; this overall utility therefore represented the total management benefit, across all objectives, expected to accrue from a given management action (table 4). Constrained optimization (Conroy and Peterson, 2013) was then used to find the management portfolio (the combination of actions, one action per salt marsh unit) that would maximize the total management benefit across all units subject to varying cost constraints for the entire the refuge. Constrained optimization was done by using integer linear programming as implemented in the Solver tool in Microsoft Excel (Kirkwood, 1997). Budget constraints were increased in $10,000 increments up to $50,000; in $50,000 increments up to $300,000; in $100,000 increments up to $1 million; and in $500,000 increments thereafter. A cost-benefit plot was used to identify the efficient frontier for resource allocation (Keeney and Raiffa, 1993), which is the set of portfolios that are not dominated by other portfolios at similar costs (or the set of portfolios with maximum total benefit for a similar cost).

**Table 3.** Possible management actions for achieving objectives within salt marsh units at the Bombay Hook National Wildlife Refuge in Delaware, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.

[SMU, salt marsh unit; 1 mile=1.609 kilometers]

| Management action | Estimated cost over 5 years | Performance metric | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Native vegetation (percent cover) | Nekton | | Tidal marsh obligate birds (summed number per point) | American black ducks use[1] | Spider density (number per square meter) | Hydrology | | Marsh surface elevation change relative to sea-level rise[3] | Herbicide application[4] |
| | | | Density (number of animals per square meter) | Species richness (number) | | | | Duration of surface flooding, deviation[2] (percent) | Surface-water salinity, deviation[2] (parts per thousand) | | |
| Leatherberry (SMU–1) | | | | | | | | | | | |
| A. No action | 0 | 98.67 | 6.29 | 11 | 6.5 | Low | 1 | 6.47 | 0 | 0 | 0 |
| B. Block Raymond Gut | 50,000 | 98.67 | 10 | 11 | 7 | Medium | 1 | 0.24 | 0 | 1 | 0 |
| C. Living shoreline along south edge of flats | 1,875,000 | 98.67 | 6.29 | 11 | 6.87 | Low | 1 | 6.47 | 0 | 0 | 0 |
| D. Living shoreline along south edge of flats with thin layer deposition | 2,175,000 | 98.67 | 10 | 11 | 7 | Medium | 15 | 6.47 | 0 | 1 | 0 |
| E. Remove or breach Shearness Pool impoundment dikes and recontour basin | 480,000 | 98.67 | 15 | 11 | 7 | Medium | 15 | 6.47 | 0 | 1 | 0 |
| F. Remove or breach Bear Swamp impoundment dikes and recontour basin | 390,000 | 98.67 | 15 | 11 | 7 | Medium | 15 | 6.47 | 0 | 1 | 0 |
| G. Recontour adjacent upland and plant to facilitate marsh migration; control *Phragmites australis* | 39,750 | 98.67 | 6.29 | 11 | 6.87 | Low | 15 | 6.47 | 0 | 1 | 0 |
| H. Stabilize cuts in bank along Sluice Ditch | 100,000 | 98.67 | 6.29 | 11 | 6.87 | Low | 15 | 6.47 | 0 | 0 | 0 |
| Bombay Hook Island North (SMU–2) | | | | | | | | | | | |
| A. No action | 0 | 92.67 | 47.03 | 11 | 6 | High | 1 | 59.32 | 2 | 0 | 0 |
| B. Delaware Bay offshore protection; living shoreline | 1,132,560 | 92.67 | 47.03 | 11 | 7.16 | High | 15 | 31.76 | 2 | 0 | 0 |
| Georges Island (SMU–3) | | | | | | | | | | | |
| A. No action | 0 | 97.33 | 42.75 | 4 | 7.31 | Medium | 1 | 5.04 | 2 | 0 | 0 |
| B. Block Raymond Gut | 50,000 | 97.33 | 45 | 5 | 7.5 | Medium | 1 | 3.24 | 2 | 1 | 0 |
| C. Thin layer deposition in marsh interior | 893,000 | 97.33 | 50 | 5 | 7.5 | Medium | 15 | 5.04 | 2 | 1 | 0 |
| D. Remove or breach Raymond Pool impoundment dikes and recontour basin | 230,000 | 97.33 | 50 | 10 | 7.5 | Medium | 15 | 5.04 | 2 | 1 | 0 |
| E. Restore oxbow hydrology along Leipsic River | 100,000 | 97.33 | 42.75 | 4 | 7.31 | Medium | 1 | 2.24 | 2 | 0 | 0 |
| F. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis* | 106,000 | 97.33 | 50 | 5 | 7.5 | Medium | 15 | 5.04 | 2 | 1 | 0 |
| G. Stabilize cuts in bank along Leipsic River | 100,000 | 97.33 | 42.75 | 4 | 7.31 | Medium | 1 | 5.04 | 2 | 0 | 0 |
| Bombay Hook Island South (SMU–4) | | | | | | | | | | | |
| A. No action | 0 | 87.17 | 55.63 | 8 | 9 | High | 15 | 68.93 | 2 | 0 | 0 |
| B. Delaware Bay offshore protection; living shoreline | 1,287,000 | 87.17 | 55.63 | 8 | 9.75 | High | 15 | 56.76 | 2 | 0 | 0 |

**Table 3.** Possible management actions for achieving objectives within salt marsh units at the Bombay Hook National Wildlife Refuge in Delaware, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[SMU, salt marsh unit; 1 mile=1.609 kilometers]

| Management action | Estimated cost over 5 years | Performance metric | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Native vegetation (percent cover) | Nekton | | Tidal marsh obligate birds (summed number per point) | American black ducks use[1] | Spider density (number per square meter) | Hydrology | | Marsh surface elevation change relative to sea-level rise[3] | Herbicide application[4] |
| | | | Density (number of animals per square meter) | Species richness (number) | | | | Duration of surface flooding, deviation[2] (percent) | Surface-water salinity, deviation[2] (parts per thousand) | | |
| Kent Island (SMU–5) | | | | | | | | | | | |
| A. No action | 0 | 99.5 | 85.1 | 8 | 9.82 | High | 1 | 60.77 | 0 | 0 | 0 |
| B. Restore sinuosity along approximately 1 mile of stream | 100,000 | 99.5 | 90 | 9 | 9.9 | High | 15 | 21.76 | 0 | 1 | 0 |
| C. Restore oxbow hydrology along Leipsic River | 100,000 | 99.5 | 85.1 | 8 | 9.82 | High | 15 | 1.76 | 0 | 1 | 0 |
| D. Stabilize cuts in bank along Leipsic River | 100,000 | 99.5 | 85.1 | 8 | 9.82 | High | 1 | 60.77 | 0 | 1 | 0 |
| Kelly Island (SMU–6) | | | | | | | | | | | |
| A. No action | 0 | 99.5 | 55.04 | 7 | 6 | Medium | 15 | 15.9 | 1 | 0 | 0 |
| B. Delaware Bay offshore protection; living shoreline | 643,000 | 99.5 | 55.04 | 7 | 6.15 | Medium | 15 | 15.9 | 1 | 0 | 0 |
| Steamboat (SMU–7) | | | | | | | | | | | |
| A. No action | 0 | 91.43 | 33.65 | 7 | 4.1 | Low | 1 | 51 | 1 | 0 | 0 |
| B. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis* | 132,500 | 91.43 | 35 | 7 | 4.5 | Low | 15 | 51 | 1 | 1 | 0 |
| C. Burn the marsh | 50,000 | 85 | 40 | 7 | 5 | Low | 1 | 51 | 1 | 1 | 0 |
| Air Force (SMU–8) | | | | | | | | | | | |
| A. No action | 0 | 98.58 | 23.09 | 6 | 5.16 | Low | 1 | 18.05 | 0 | 0 | 0 |
| B. Burn the marsh | 50,000 | 90 | 30 | 6 | 6 | Low | 1 | 18.05 | 0 | 1 | 0 |

[1]Relative abundance for refuge during wintering waterfowl season.

[2]Measures absolute deviation from reference point representing ideal condition.

[3]Measures change relative to sea-level rise: 0, less than sea-level rise; 1, greater than or equal to sea-level rise.

[4]Measures level of herbicide applied: 0, none applied; 1, some applied.

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh units at the Bombay Hook National Wildlife Refuge in Delaware.

[Numeric table entries are weighted utilities, which were calculated as raw utilities × objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 1). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 2). The total management benefit for each action is the sum of weighted utilities across all performance metrics. SMU, salt marsh unit]

| Management action | Performance metric | | | | | | | | | | Total management benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Native vegetation | Nekton | | Tidal marsh obligate birds | American black ducks | Spider density | Hydrology | | Marsh surface elevation change | Herbicide application | |
| | | Density | Species richness | | | | Duration of surface flooding | Surface-water salinity | | | |
| Leatherberry (SMU–1) | | | | | | | | | | | |
| A. No action | 0.119 | 0.006 | 0.045 | 0.066 | 0 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.516 |
| B. Block Raymond Gut | 0.119 | 0.009 | 0.045 | 0.071 | 0.075 | 0 | 0.11 | 0.11 | 0.22 | 0.06 | 0.819 |
| C. Living shoreline along south edge of flats | 0.119 | 0.006 | 0.045 | 0.069 | 0 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.52 |
| D. Living shoreline along south edge of flats with thin layer deposition | 0.119 | 0.009 | 0.045 | 0.071 | 0.075 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.864 |
| E. Remove or breach Shearness Pool impoundment dikes and recontour basin | 0.119 | 0.013 | 0.045 | 0.071 | 0.075 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.868 |
| F. Remove or breach Bear Swamp impoundment dikes and recontour basin | 0.119 | 0.013 | 0.045 | 0.071 | 0.075 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.868 |
| G. Recontour adjacent upland and plant to facilitate marsh migration; control *Phragmites australis* | 0.119 | 0.006 | 0.045 | 0.069 | 0 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.785 |
| H. Stabilize cuts in bank along Sluice Ditch | 0.119 | 0.006 | 0.045 | 0.069 | 0 | 0.045 | 0.11 | 0.11 | 0 | 0.06 | 0.565 |
| Bombay Hook Island North (SMU–2) | | | | | | | | | | | |
| A. No action | 0.117 | 0.031 | 0.045 | 0.061 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.524 |
| B. Delaware Bay offshore protection; living shoreline | 0.117 | 0.031 | 0.045 | 0.072 | 0.1 | 0.045 | 0.03 | 0.11 | 0 | 0.06 | 0.611 |
| Georges Island (SMU–3) | | | | | | | | | | | |
| A. No action | 0.119 | 0.03 | 0.016 | 0.074 | 0.075 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.594 |
| B. Block Raymond Gut | 0.119 | 0.031 | 0.02 | 0.076 | 0.075 | 0 | 0.11 | 0.11 | 0.22 | 0.06 | 0.821 |
| C. Thin layer deposition in marsh interior | 0.119 | 0.033 | 0.02 | 0.076 | 0.075 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.868 |
| D. Remove or breach Raymond Pool impoundment dikes and recontour basin | 0.119 | 0.033 | 0.041 | 0.076 | 0.075 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.888 |
| E. Restore oxbow hydrology along Leipsic River | 0.119 | 0.03 | 0.016 | 0.074 | 0.075 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.594 |
| F. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis* | 0.119 | 0.033 | 0.02 | 0.076 | 0.075 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.868 |
| G. Stabilize cuts in bank along Leipsic River | 0.119 | 0.03 | 0.016 | 0.074 | 0.075 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.594 |

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh units at the Bombay Hook National Wildlife Refuge in Delaware.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities × objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 1). Objective weights for individual metrics were calculated as the product of the weights on the branch of the objectives hierarchy leading to each metric (table 2). The total management benefit for each action is the sum of weighted utilities across all performance metrics. SMU, salt marsh unit]

| Management action | Performance metric | | | | | | | | | | Total management benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Native vegetation | Nekton | | Tidal marsh obligate birds | American black ducks | Spider density | Hydrology | | Marsh surface elevation change | Herbicide application | |
| | | Density | Species richness | | | | Duration of surface flooding | Surface-water salinity | | | |
| Bombay Hook Island South (SMU–4) | | | | | | | | | | | |
| A. No action | 0.115 | 0.035 | 0.033 | 0.091 | 0.1 | 0.045 | 0 | 0.11 | 0 | 0.06 | 0.588 |
| B. Delaware Bay offshore protection; living shoreline | 0.115 | 0.035 | 0.033 | 0.098 | 0.1 | 0.045 | 0 | 0.11 | 0 | 0.06 | 0.596 |
| Kent Island (SMU–5) | | | | | | | | | | | |
| A. No action | 0.12 | 0.044 | 0.033 | 0.099 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.566 |
| B. Restore sinuosity along approximately 1 mile of stream | 0.12 | 0.045 | 0.037 | 0.1 | 0.1 | 0.045 | 0.067 | 0.11 | 0.22 | 0.06 | 0.904 |
| C. Restore oxbow hydrology along Leipsic River | 0.12 | 0.044 | 0.033 | 0.099 | 0.1 | 0.045 | 0.11 | 0.11 | 0.22 | 0.06 | 0.941 |
| D. Stabilize cuts in bank along Leipsic River | 0.12 | 0.044 | 0.033 | 0.099 | 0.1 | 0 | 0 | 0.11 | 0.22 | 0.06 | 0.786 |
| Kelly Island (SMU–6) | | | | | | | | | | | |
| A. No action | 0.12 | 0.035 | 0.029 | 0.061 | 0.075 | 0.045 | 0.088 | 0.11 | 0 | 0.06 | 0.622 |
| B. Delaware Bay offshore protection; living shoreline | 0.12 | 0.035 | 0.029 | 0.062 | 0.075 | 0.045 | 0.088 | 0.11 | 0 | 0.06 | 0.624 |
| Steamboat (SMU–7) | | | | | | | | | | | |
| A. No action | 0.116 | 0.025 | 0.029 | 0.041 | 0 | 0 | 0 | 0.11 | 0 | 0.06 | 0.381 |
| B. Recontour adjacent upland and plant to facilitate marsh migration; control *P. australis* | 0.116 | 0.026 | 0.029 | 0.045 | 0 | 0.045 | 0 | 0.11 | 0.22 | 0.06 | 0.651 |
| C. Burn the marsh | 0.113 | 0.028 | 0.029 | 0.051 | 0 | 0 | 0 | 0.11 | 0.22 | 0.06 | 0.611 |
| Air Force (SMU–8) | | | | | | | | | | | |
| A. No action | 0.119 | 0.019 | 0.025 | 0.052 | 0 | 0 | 0.08 | 0.11 | 0 | 0.06 | 0.465 |
| B. Burn the marsh | 0.116 | 0.023 | 0.025 | 0.061 | 0 | 0 | 0.08 | 0.11 | 0.22 | 0.06 | 0.694 |

# Results of Constrained Optimization

Management actions identified to improve marsh integrity at the Bombay Hook National Wildlife Refuge included strategies to restore or enhance physical marsh features, protect shorelines from erosion, and manage native marsh vegetation (table 3). Within individual management units, for costs ranging from $0 to $2.175 million, the estimated management benefits for specific actions across all metrics (measured as weighted utilities) ranged from 0.381 to 0.941 (tables 3 and 4). Within each unit, the action with both the lowest management benefit and lowest cost was the no-action option (action A).

Constrained optimization was applied to identify the optimal management portfolios over 5 years for a range of total costs to the refuge. As total cost increased from $0 (no action in any unit) to approximately $4 million, the total management benefit increased from 4.277 to 5.873 (table 5). Graphical analysis showed a consistent increase in management benefit as costs increased to $300,000 (fig. 3, portfolio 8). Expenditures beyond this amount would yield diminishing returns on investment, and portfolio 12, at a total cost of about $800,000, dominated the costlier portfolios in terms of cost-benefit tradeoffs (fig. 3).

Several patterns emerged relative to management actions selected for yielding the best returns on investments within the optimal set of portfolios (table 5, portfolios 2 through 8). At Leatherberry (SMU–1) and Georges Island (SMU–3), the optimal portfolios consistently included either blocking a man-made waterway (Raymond Gut) or recontouring the adjacent upland and planting to facilitate marsh migration. At three units (Bombay Hook Island North [SMU–2], Bombay Hook Island South [SMU–4], and Kelly Island [SMU–6]), taking no action was preferable to the high expenditures ($643,000 to $1.287 million) and relatively low increases in management benefit (0.002 to 0.087) associated with installation of offshore

**Table 5.** Actions included in various management portfolios to maximize the total management benefits subject to increasing cost constraints in the Bombay Hook National Wildlife Refuge in Delaware.

[Letter designations for actions refer to specific actions and are listed in tables 3 and 4. Portfolios represent the combination of actions, one per salt marsh management unit, that maximized the total management benefit across all units subject to a refugewide cost constraint. The management actions constituting individual portfolios were selected using constrained optimization. SMU, salt marsh unit]

| Portfolio | Salt marsh management unit | | | | | | | | Total cost (dollars) | Total management benefit |
|---|---|---|---|---|---|---|---|---|---|---|
| | Leatherberry (SMU–1) | Bombay Hook Island North (SMU–2) | Georges Island (SMU–3) | Bombay Hook Island South (SMU–4) | Kent Island (SMU–5) | Kelly Island (SMU–6) | Steamboat (SMU–7) | Air Force (SMU–8) | | |
| 1 | A | A | A | A | A | A | A | A | 0 | 4.277 |
| 2 | G | A | A | A | A | A | A | A | 39,750 | 4.525 |
| 3 | B | A | A | A | A | A | A | A | 50,000 | 4.559 |
| 4 | B | A | A | A | A | A | C | A | 100,000 | 4.789 |
| 5 | B | A | A | A | A | A | C | B | 150,000 | 5.018 |
| 6 | B | A | B | A | A | A | C | B | 200,000 | 5.245 |
| 7 | B | A | A | A | C | A | C | B | 250,000 | 5.393 |
| 8 | B | A | B | A | C | A | C | B | 300,000 | 5.620 |
| 9 | B | A | F | A | C | A | C | B | 356,000 | 5.667 |
| 10 | B | A | F | A | C | A | B | B | 438,500 | 5.708 |
| 11 | B | A | D | A | C | A | B | B | 562,500 | 5.728 |
| 12 | F | A | F | A | C | A | B | B | 778,500 | 5.756 |
| 13 | E | A | F | A | C | A | B | B | 868,500 | 5.756 |
| 14 | F | A | D | A | C | A | B | B | 902,500 | 5.777 |
| 15 | F | B | F | A | C | A | B | B | 1,911,060 | 5.843 |
| 16 | F | B | D | A | C | A | B | B | 2,035,060 | 5.864 |
| 17 | E | B | D | A | C | B | B | B | 2,768,060 | 5.865 |
| 18 | E | B | D | B | C | A | B | B | 3,412,060 | 5.871 |
| 19 | F | B | D | B | C | B | B | B | 3,965,060 | 5.873 |
| 20 | E | B | D | B | C | B | B | B | 4,055,060 | 5.873 |

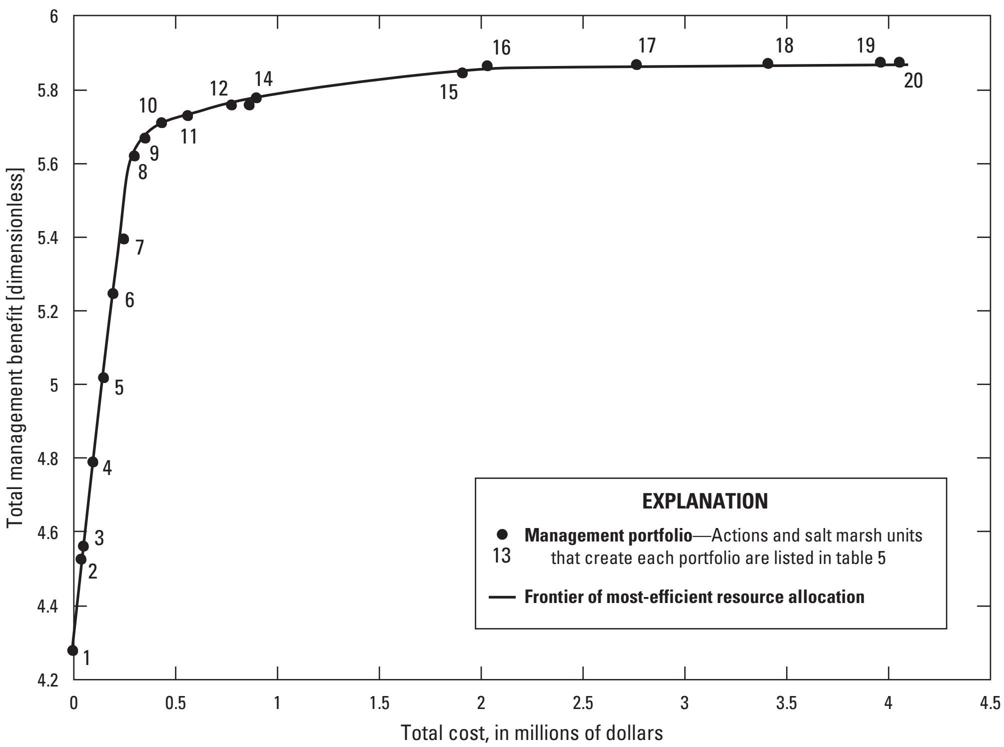



**Figure 3.** Predicted total management benefit of various portfolios, expressed as weighted utilities, relative to total annual cost at the Bombay Hook National Wildlife Refuge in Delaware. Each portfolio (dot with number) represents a combination of eight management actions, one per salt marsh unit, as identified in table 5. The line represents the efficient frontier for resource allocation.

protection or living shorelines (shorelines that use plants or other natural elements to stabilize estuarine coasts, bays, or tributaries) in Delaware Bay. For other units, actions related to restoring oxbow hydrology along the Leipsic River (Kent Island [SMU–5]), recontouring adjacent upland areas and planting to facilitate marsh migration (Steamboat [SMU–7]), and burning the marsh (Steamboat [SMU–7] and Air Force [SMU–8]) were consistently selected. In contrast, some management actions were never included in an optimal portfolio. For example, although bank stabilization was identified to reduce the effect of erosion on marsh edges within three units (Leatherberry [SMU–1], Georges Island [SMU–3], and Kent Island [SMU–5]), this action was never selected. Similarly, the optimal portfolios never included actions that incorporated thin layer deposition (possible actions within Leatherberry [SMU–1] and Georges Island [SMU–3]).

Examination of constrained optimization results in terms of individual performance metrics reveals the relative effects of implementing a certain portfolio on specific management objectives at the refuge scale. For example, implementing portfolio 8 would be predicted to yield modest gains in management benefits for some metrics, but would yield great gains in the capacity of marsh elevation to keep pace with sea-level rise (fig. 4). Ecologically, the combination of actions in this portfolio would result in an average 14-percent increase in nekton density (averaged across all units), an average 6-percent increase in tidal marsh obligate bird counts, an average 1-percent decrease in native vegetation cover, and an increased capacity for marsh elevation to keep pace with sea-level rise in five of the eight management units (derived as the average difference between the predicted metric scores for the actions implemented in portfolio 8 and the no action alternative, using scores listed in table 3).

# Considerations for Optimizing Salt Marsh Management

A regional structured decision-making framework for salt marshes at NWRs in the northeastern United States was applied by the USGS, in cooperation with the FWS to develop a tool for optimizing management decisions at the Bombay Hook National Wildlife Refuge. Use of the existing regional framework and a rapid-prototyping approach permitted NWR biologists and managers, FWS regional authorities, and research scientists to construct a decision model for the refuge within the confines of a 1.5-day workshop. This preliminary prototype provides a local framework for decision making while revealing information needs for future iterations.

The suite of potential management actions and predicted outcomes included in this prototype (table 3) were based on current understanding of the Bombay Hook National Wildlife Refuge salt marshes and hypothesized process-response pathways. Tidal flooding is the predominant physical control on the structure and function of salt marsh ecosystems (Pennings and Bertness, 2001), and there is widespread scientific effort to elucidate how salt marshes will respond to accelerating rates of sea-level rise (Kirwan and Megonigal, 2013; Roman, 2017). Results of ongoing hydrodynamic modeling at the Bombay

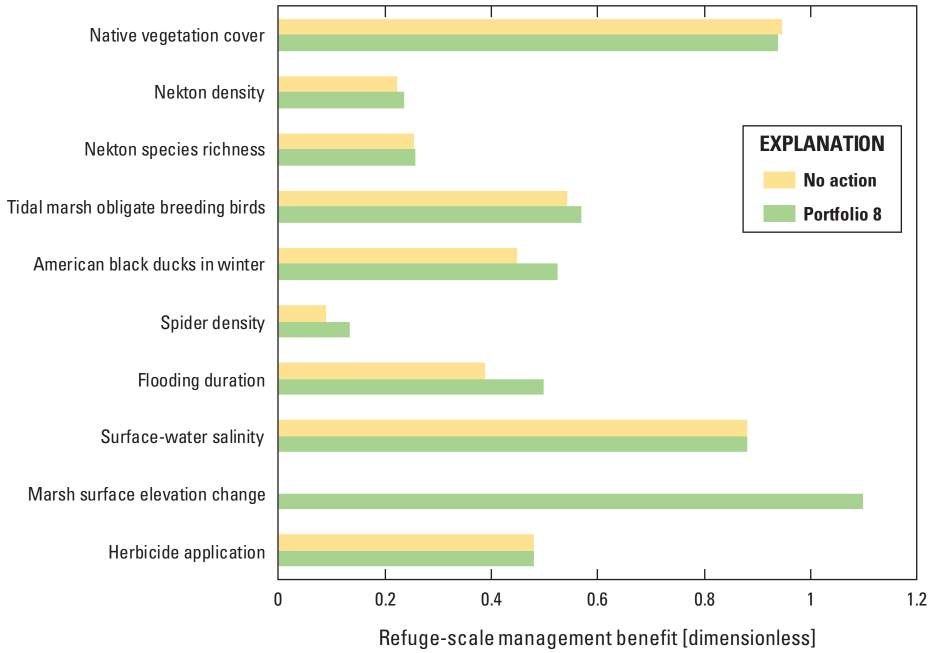



**Figure 4.** Predicted management benefit at the refuge scale for individual performance metrics, expressed as weighted utilities, resulting from implementation of the management actions included in portfolio 8, in comparison to the management benefit from the baseline "no-action" portfolio at the Bombay Hook National Wildlife Refuge in Delaware. The actions included in each portfolio are listed in table 5.

Hook National Wildlife Refuge could be expected to influence the types of management actions considered to enhance marsh sustainability, as well as the predicted responses to management interventions. In addition, during construction of the regional decision model, lack of widely available data on rates of vertical marsh growth led to the adoption of a coarse scale of measurement for change in marsh surface elevation relative to sea-level rise (table 1). Therefore, recent data on salt marsh accretion and elevation change at the Bombay Hook National Wildlife Refuge (McDowell, 2017) could also improve management predictions.

Results of constrained optimizations (table 5) based on the objectives, management actions, and predicted outcomes included in this prototype indicate possible areas for future consideration. For example, thin-layer deposition of dredged sediments on the marsh surface is increasingly proposed to enhance sustainability of northeastern salt marshes (Wigand and others, 2017), but this management action was never included in an optimal portfolio. Multiple, interacting factors influence the long-term success of sediment additions in prolonging marsh integrity, and coastal managers are currently [2018] evaluating the efficacy as a management strategy (Roman, 2017). Increased scientific understanding of conditions under which thin-layer deposition enhances marsh resilience will likely improve management predictions. Secondly, although marsh loss through shore-face erosion is a predominant management concern at the Bombay Hook National Wildlife Refuge, bank stabilization typically had a small effect on the predicted total management benefit over the no-action alternative (table 3, Leatherberry [SMU–1] and Georges Island [SMU–3]) and was not included in any optimal portfolio. This result may lead decision makers to consider deconstructing the objective on maintaining the extent of the marsh platform into subobjectives and performance metrics related to both horizonal and vertical gains and losses. Finally, the constrained optimizations performed here were based on approximations of management costs. As salt marsh management is implemented around the region a list of actual expenses can be compiled, so that future iterations of the decision model can include more accurate cost estimates.

The prototype model for the Bombay Hook National Wildlife Refuge is a useful tool for decision making that can be updated in the future with new data and information. The spatial and temporal variability inherent in parameter estimates were not quantified during rapid prototyping. Previously, preliminary sensitivity analysis revealed little effect of incorporating ecological variation in abundance of marsh obligate breeding birds on the optimal solutions for Prime Hook National Wildlife Refuge (Neckles and others, 2015), lending confidence to use of this framework for decision making. Future monitoring of salt marsh integrity performance metrics will be useful to refine baseline parameter estimates, and feedback from measured responses to management actions around the region will help reduce uncertainties surrounding management predictions. The structured decision-making framework applied here to the Bombay Hook National Wildlife Refuge is based on a hierarchy of regional objectives and regional value functions relating performance metrics to perceived management benefits. Elements of the decision model could be further adapted, for example through differential weighting of objectives or altered value functions, to reflect specific, local management goals and mandates. Future optimization analyses that use this framework could also incorporate additional constraints on action selection, such as ensuring that particular actions within individual salt marsh units are included in optimal management portfolios, to further tailor the model to refuge-specific needs.

## References Cited

Blomquist, S.M., Johnson, T.D., Smith, D.R., Call, G.P., Miller, B.N., Thurman, W.M., McFadden, J.E., Parkin, M.J., and Boomer, G.S., 2010, Structured decision-making and rapid prototyping to plan a management response to an invasive species: Journal of Fish and Wildlife Management, v. 1, no. 1, p. 19–32. [Also available at https://doi.org/10.3996/JFWM-025.]

Conroy, M.J., and Peterson, J.T., 2013, Decision making in natural resource management—A structured, adaptive approach: West Sussex, United Kingdom, John Wiley and Sons, Ltd., 456 p.

Garrard, G.E., Rumpff, L., Runge, M.C., and Converse, S.J., 2017, Rapid prototyping for decision structuring—An efficient approach to conservation decision analysis, *in* Bunnefeld, N., Nicholson, E., and Milner-Gulland, E.J., eds., Decision-making in conservation and natural resource management: Cambridge, United Kingdom, Cambridge University Press, p. 46–64.

Gedan, K.B., Altieri, A.H., and Bertness, M.D., 2011, Uncertain future of New England salt marshes: Marine Ecology Progress Series, v. 434, p. 229–237. [Also available at https://doi.org/10.3354/meps09084.]

Gedan, K.B., Silliman, B.R., and Bertness, M.D., 2009, Centuries of human-driven change in salt marsh ecosystems: Annual Review of Marine Science, v. 1, no. 1, p. 117–141. [Also available at https://doi.org/10.1146/annurev.marine.010908.163930.]

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., and Ohlson, D., 2012, Structured decision making—A practical guide to environmental management choices: West Sussex, United Kingdom, John Wiley and Sons, Ltd., 299 p.

Gregory, R.S., and Keeney, R.L., 2002, Making smarter environmental management decisions: Journal of the American Water Resources Association, v. 38, no. 6, p. 1601–1612. [Also available at https://doi.org/10.1111/j.1752-1688.2002.tb04367.x.]

Hammond, J.S., Keeney, R.L., and Raiffa, H., 1999, Smart choices—A practical guide to making better life decisions: Boston, Harvard Business School Press, 242 p.

Keeney, R.L., and Raiffa, H., 1993, Decisions with multiple objectives—Preferences and value tradeoffs: Cambridge University Press, 569 p.

Kirkwood, C.W., 1997, Strategic decision making—Multiobjective decision analysis with spreadsheets: Belmont, Calif., Duxbury Press, 345 p.

Kirwan, M.L., and Megonigal, J.P., 2013, Tidal wetland stability in the face of human impacts and sea-level rise: Nature, v. 504, no. 7478, p. 53–60. [Also available at https://doi.org/10.1038/nature12856.]

McDowell, C., 2017, Marsh sediment accumulation and accretion on a rapidly retreating estuarine coast: Newark, University of Delaware, M.S. thesis, 66 p., appendixes, accessed July 24, 2018, at http://udspace.udel.edu/handle/19716/21246.

Neckles, H.A., Guntenspergen, G.R., Shriver, W.G., Danz, N.P., Wiest, W.A., Nagel, J.L., and Olker, J.H., 2013, Identification of metrics to monitor salt marsh integrity on national wildlife refuges in relation to conservation and management objectives—Final report to U.S. Fish and Wildlife Service, Northeast Region: U.S. Geological Survey Patuxent Wildlife Research Center, 226 p., accessed May 1, 2018, at https://ecos.fws.gov/ServCat/Reference/Profile/37795.

Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]

Pennings, S.C., and Bertness, M.D., 2001, Salt marsh communities, *in* Bertness, M.D., Gaines, S.D., and Hay, M.E., eds., Marine community ecology: Sunderland, Mass., Sinauer Associates, p. 289–316.

Roman, C.T., 2017, Salt marsh sustainability—Challenges during an uncertain future: Estuaries and Coasts, v. 40, no. 3, p. 711–716. [Also available at https://doi.org/10.1007/s12237-016-0149-2.]

U.S. Fish and Wildlife Service (FWS), 2013, Bombay Hook National Wildlife Refuge: U.S. Fish and Wildlife Service website, accessed June 15, 2018, at https://www.fws.gov/refuge/Bombay_Hook/wildlife_and_habitat/index.html.

U.S. Fish and Wildlife Service (FWS), 2014, Bombay Hook National Wildlife Refuge: U.S. Fish and Wildlife Service refuge brochure, 10 p., accessed June 15, 2018, at https://www.fws.gov/uploadedFiles/Region_5/NWRS/South_Zone/Coastal_Delaware_Complex/Bombay_Hook/PDFs/NewBHgeneralbrochure.pdf.

U.S. Fish and Wildlife Service (FWS), 2016, A brief history of Bombay Hook National Wildlife Refuge: U.S. Fish and Wildlife Service, 8 p., accessed June 15, 2018, at https://www.fws.gov/uploadedFiles/Region_5/NWRS/South_Zone/Coastal_Delaware_Complex/Bombay_Hook/History.pdf.

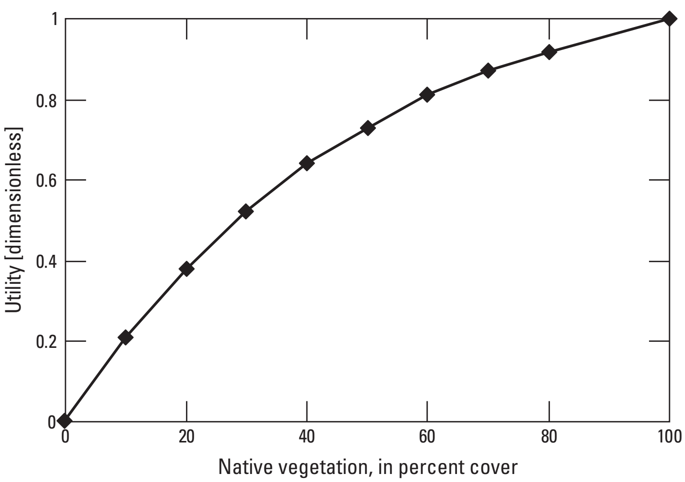
Wigand, C., Ardito, T., Chaffee, C., Ferguson, W., Paton, S., Raposa, K., Vandemoer, C., and Watson, E., 2017, A climate change adaptation strategy for management of coastal marsh systems: Estuaries and Coasts, v. 40, no. 3, p. 682–693. [Also available at https://doi.org/10.1007/s12237-015-0003-y.]

# Appendix 1. Utility Functions for the Bombay Hook National Wildlife Refuge

Utilities [$u(x)$] are derived as monotonically increasing, monotonically decreasing, or step functions over the range of performance metric $x$. In the functions below, $x$, *Low*, *High*, and $\rho$ are expressed in performance metric units; *Low* and *High* represent the endpoints of the given metric range for the Bombay Hook National Wildlife Refuge; and $\rho$ represents a shape parameter derived by stakeholder elicitation (Neckles and others, 2015). Break points in step functions were also derived by stakeholder elicitation (Neckles and others, 2015).

## Reference Cited

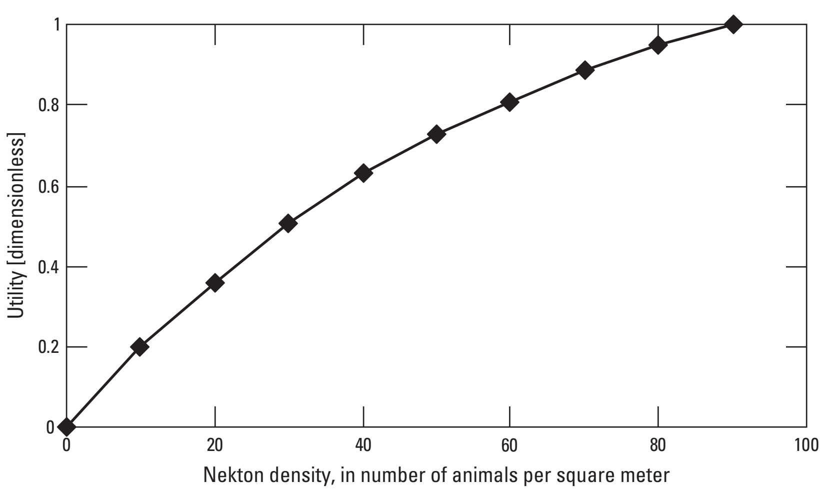
Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]




$$u(x) = \frac{1 - e^{\frac{-(x-Low)}{\rho}}}{1 - e^{\frac{-(High-Low)}{\rho}}}$$

where
*Low* = 0
*High* = 100
$\rho$ = 50

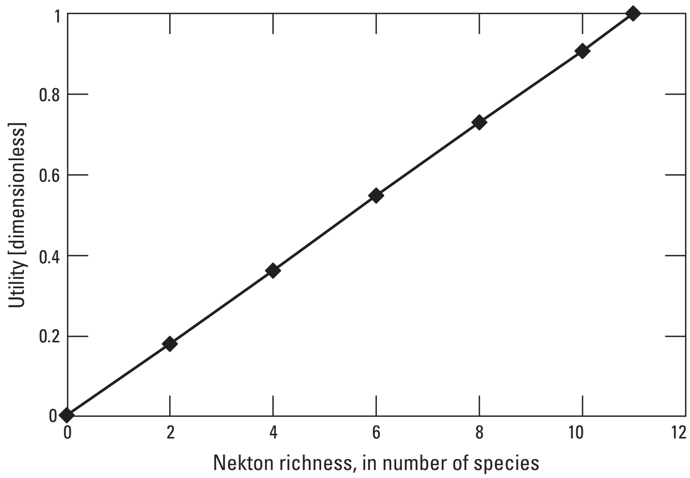
**Figure 1.1.** Native vegetation at the Bombay Hook National Wildlife Refuge, Delaware.




$$u(x) = \frac{1 - e^{\frac{-(x-Low)}{\rho}}}{1 - e^{\frac{-(High-Low)}{\rho}}}$$

where
*Low* = 0
*High* = 90
$\rho$ = 60

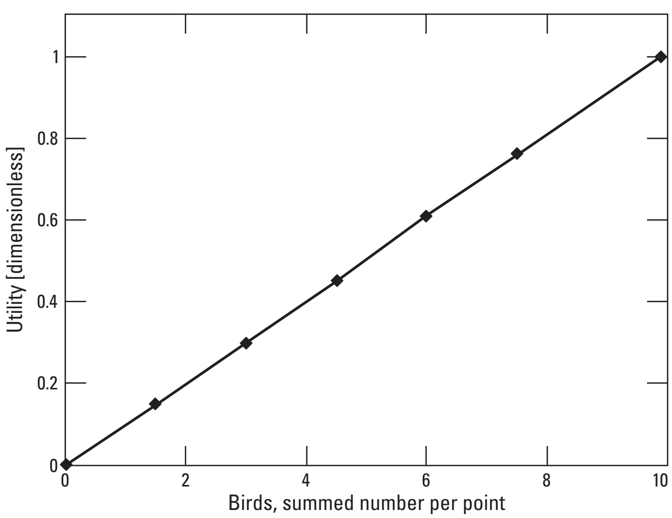
**Figure 1.2.** Native Nekton density at the Bombay Hook National Wildlife Refuge, Delaware.




$$u(x) = \frac{x - Low}{High - Low}$$

where
$Low = 0$
$High = 11$

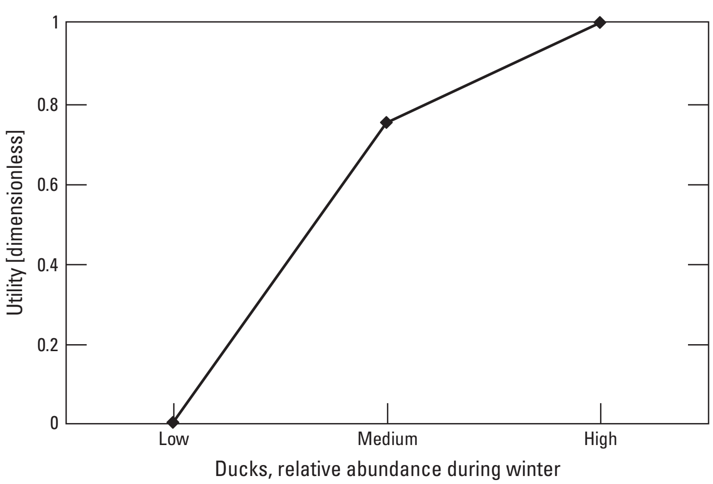
**Figure 1.3.** Native Nekton species richness at the Bombay Hook National Wildlife Refuge, Delaware.




$$u(x) = \frac{x - Low}{High - Low}$$

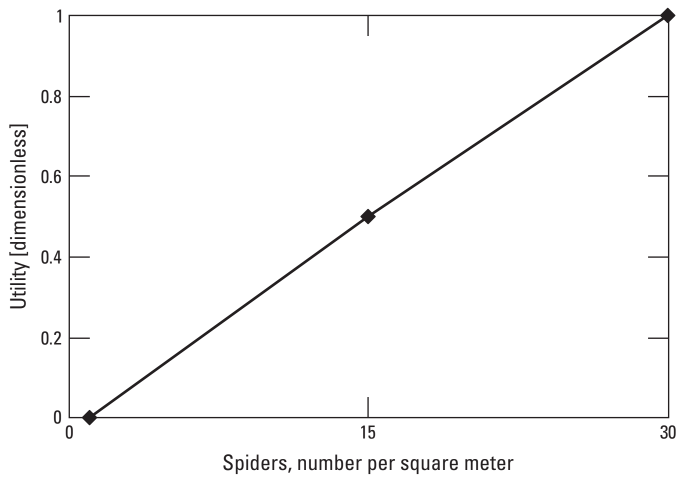
where
$Low = 0$
$High = 9$

**Figure 1.4.** Tidal marsh obligate birds at the Bombay Hook National Wildlife Refuge, Delaware.




If $x = Low$, then $u(x) = 0$
If $x = Medium$, then $u(x) = 0.75$
If $x = High$, then $u(x) = 1$

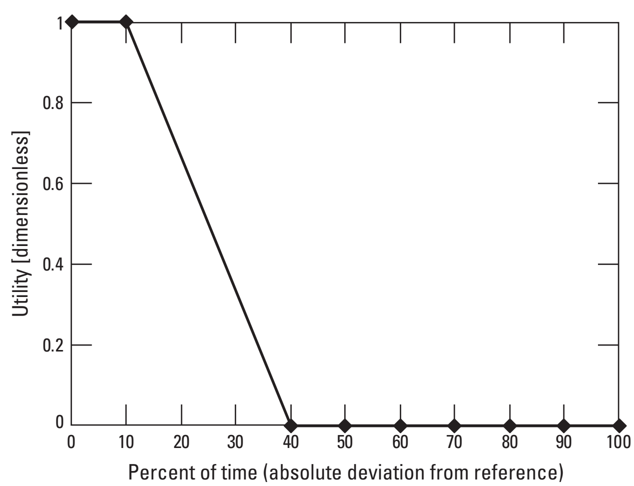
**Figure 1.5.** American black ducks at the Bombay Hook National Wildlife Refuge, Delaware.




If $x \leq 15$, then $u(x) = 0.5 \times \frac{x-1}{15}$

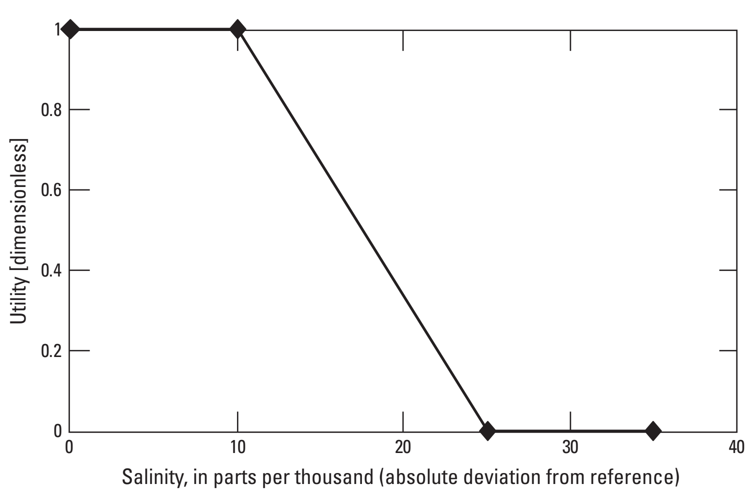
If $x > 15$, then $u(x) = 0.5 + (0.5 \times \frac{x-15}{15})$

**Figure 1.6.** Marsh spiders at the Bombay Hook National Wildlife Refuge, Delaware.



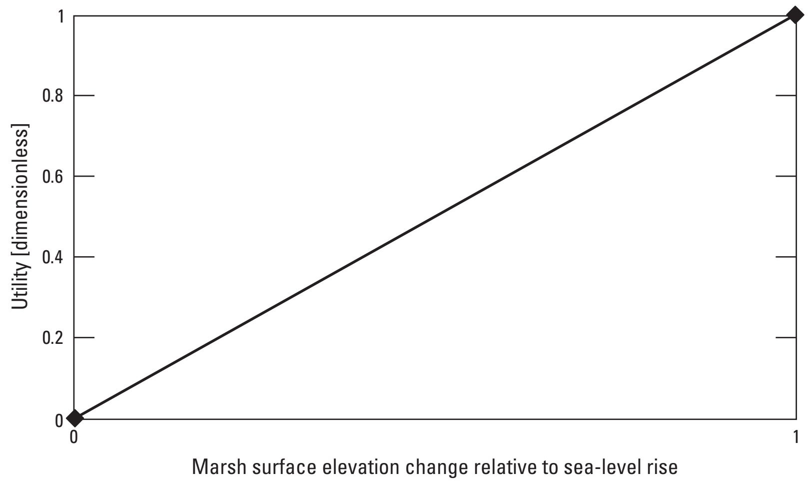

If $x \leq 10$, then $u(x) = 1$
If $x \geq 40$, then $u(x) = 0$
If $10 < x < 40$, then $u(x) = 1 - \frac{x-10}{30}$

**Figure 1.7.** Duration of surface flooding at the Bombay Hook National Wildlife Refuge, Delaware.




If $x \leq 10$, then $u(x) = 1$
If $x \geq 25$, then $u(x) = 0$
If $10 < x < 25$, then $u(x) = 1 - \frac{x-10}{15}$

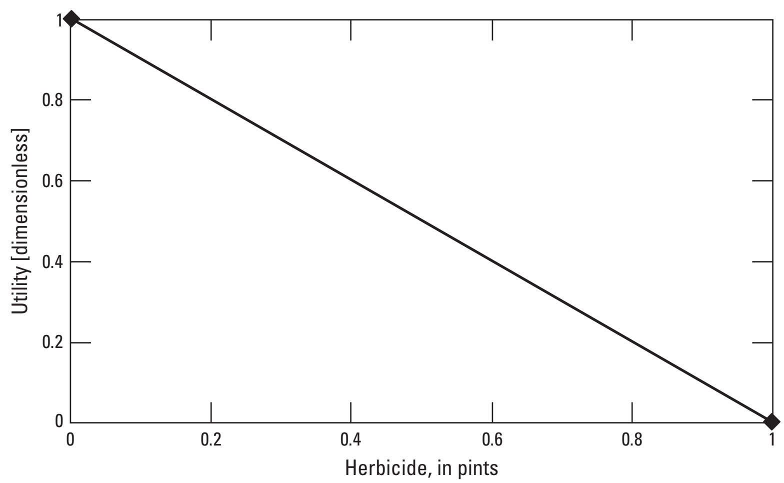
**Figure 1.8.** Salinity of surface water at the Bombay Hook National Wildlife Refuge, Delaware.




$$u(x) = \frac{x - Low}{High - Low}$$

where
*Low* = 0, lower than sea-level rise
*High* = 1, above sea-level rise

**Figure 1.9.** Change in marsh surface elevation relative to sea-level rise at the Bombay Hook National Wildlife Refuge, Delaware.




$$u(x) = \frac{High - x}{High - Low}$$

where
*Low* = 0
*High* = 1

**Figure 1.10.** Application of herbicides at the Bombay Hook National Wildlife Refuge, Delaware.

For more information, contact:
U.S. Geological Survey
Director, Patuxent Wildlife Research Center
12100 Beech Forest Road
Laurel, MD 20708-4039
https://www.usgs.gov/centers/pwrc

Publishing support provided by the Pembroke and
West Trenton Publishing Service Centers

Neckles and others—**Optimization of Salt Marsh Management at the Bombay Hook National Wildlife Refuge**—Open-File Report 2018–1160

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20181160