# Optimization of Salt Marsh Management at the Rhode Island National Wildlife Refuge Complex Through Use of Structured Decision Making

Open-File Report 2019–1103

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

**Cover.** Photograph of a salt marsh at the John H. Chafee National Wildlife Refuge in Rhode Island; photograph by the U.S. Fish and Wildlife Service.

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

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James F. Reilly II, Director

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# Contents



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# Conversion Factors

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |

# Datum

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 |
| USGS | U.S. Geological Survey |

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## 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 Rhode Island National Wildlife Refuge Complex. Refuge biologists, refuge managers, and research scientists identified multiple potential management actions to improve the ecological integrity of nine salt marsh management units within the refuge complex 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 management 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 may increase consistently up to approximately $150,000, but that further expenditures may yield diminishing return on investment. Management actions in optimal portfolios at total costs less than $150,000 included digging runnels (by hand or machine) on the marsh surface to improve drainage in eight management units, applying sediment to the marsh surface (thin layer deposition) in one management unit, constructing islands for use by tidal marsh obligate birds in two management units, and controlling *Phragmites australis* in one management unit. The management benefits were derived from expected improvements in the capacity for marsh elevation to keep pace with sea-level rise and increases in numbers of spiders (as an indicator of trophic health) and tidal marsh obligate birds. The prototype presented here provides a framework for decision making at the Rhode Island National Wildlife Refuge Complex that can be updated as new data and information become available. Insights from this process may also be useful to inform future habitat management planning at the refuge.

## 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,

[1]U.S. Geological Survey.

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

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 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 Rhode Island National Wildlife Refuge Complex consists of five refuges in coastal Rhode Island, three of which protect nearly 100 hectares of brackish and salt marsh located along or near the Atlantic Ocean (the John H. Chafee National Wildlife Refuge, hereafter referred to as the “Chafee” National Wildlife Refuge, fig. 2; the Ninigret National Wildlife Refuge, fig. 3; and the Sachuest Point National Wildlife Refuge, fig. 4). The marsh on each refuge provides critical nesting, migratory, and wintering habitat for birds of highest conservation priority, including saltmarsh sparrows and American black ducks, in the U.S. North American Bird Conservation Initiative’s bird conservation region for the New England and mid-Atlantic coast (FWS 2002a, b, c; Steinkamp, 2008; Association of Fish and Wildlife Agencies, 2019). The primary threats to this habitat are marsh submergence associated with rising sea level, expansion of the invasive reed *Phragmites australis* (hereafter referred to as *Phragmites*), shoreline erosion, and habitat loss, fragmentation, and degradation associated with increasing human activity in the land surrounding the refuge (FWS 2002a, b, c). Salt marsh management goals for the refuge focus on maintaining high-quality habitat for breeding, migrating, and wintering birds and restoring and enhancing habitat. 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 Rhode Island National Wildlife Refuge Complex. 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 nine salt marsh management units at the refuge complex (figs. 2–4), approximate costs 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 Rhode Island National Wildlife Refuge Complex.

## Description of Study Area

The refuges of the Rhode Island National Wildlife Refuge Complex are located along or near Block Island Sound in coastal Rhode Island. The complex’s salt marsh is divided into five management units within the Chafee National Wildlife Refuge (Northeast Marsh, Southeast Marsh, Southwest Marsh, Sedge Island, and North Middlebridge) (fig. 2); two management units within the Ninigret National Wildlife Refuge (Barrier Beach, Mainland) (fig. 3); and two management units within the Sachuest Point National Wildlife Refuge (North Marsh, Restored Marsh) (fig. 4). Most of the land immediately surrounding the management units consists of natural land uses classified within the 2011 National Land Cover Database as categories other than agricultural or developed (U.S. Geological Survey, 2014; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017), although two of the units at the Chafee National Wildlife Refuge have substantial suburban development within 1 kilometer of the marsh edge (Southwest Marsh, North Middlebridge). The predominant upland habitat is deciduous forest and native and non-native shrublands (FWS 2002a, b, c). Many of the management units are affected by a long history of hydrologic alterations and subsidence, with consequent retention of upland freshwater discharge and prolonged flooding. In addition, historical ditching is moderately dense within four management units (Northeast and Southwest Marshes at the Chafee National Wildlife Refuge; both units at the Sachuest Point National Wildlife Refuge). Invasive plants are in most of the management units, and the spread of *Phragmites* is a management concern particularly in the units at Ninigret National Wildlife Refuge and Sachuest Point National Wildlife Refuge (FWS 2002b, c; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017). During 2012–16, average surface-water salinities in the summer ranged from about 15 to about 38 parts per thousand within the marshes (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017), making the surface water mesohaline to euhaline (as defined by Cowardin and others, 1979).

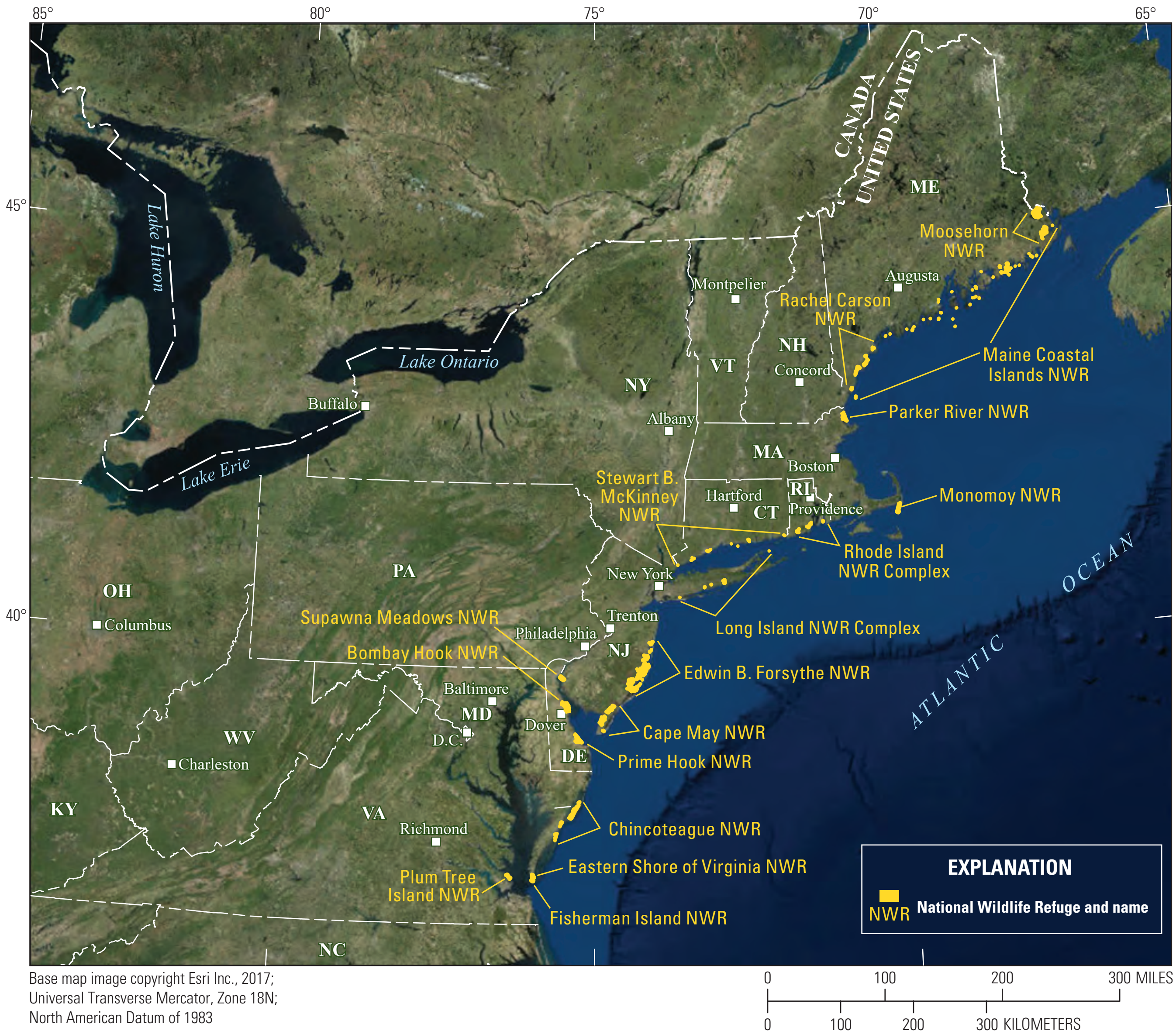


**Figure 1.** National wildlife refuges and national wildlife refuge complexes of the U.S. Fish and Wildlife Service where salt marsh integrity was assessed from 2012 to 2016 using the regional monitoring protocol.

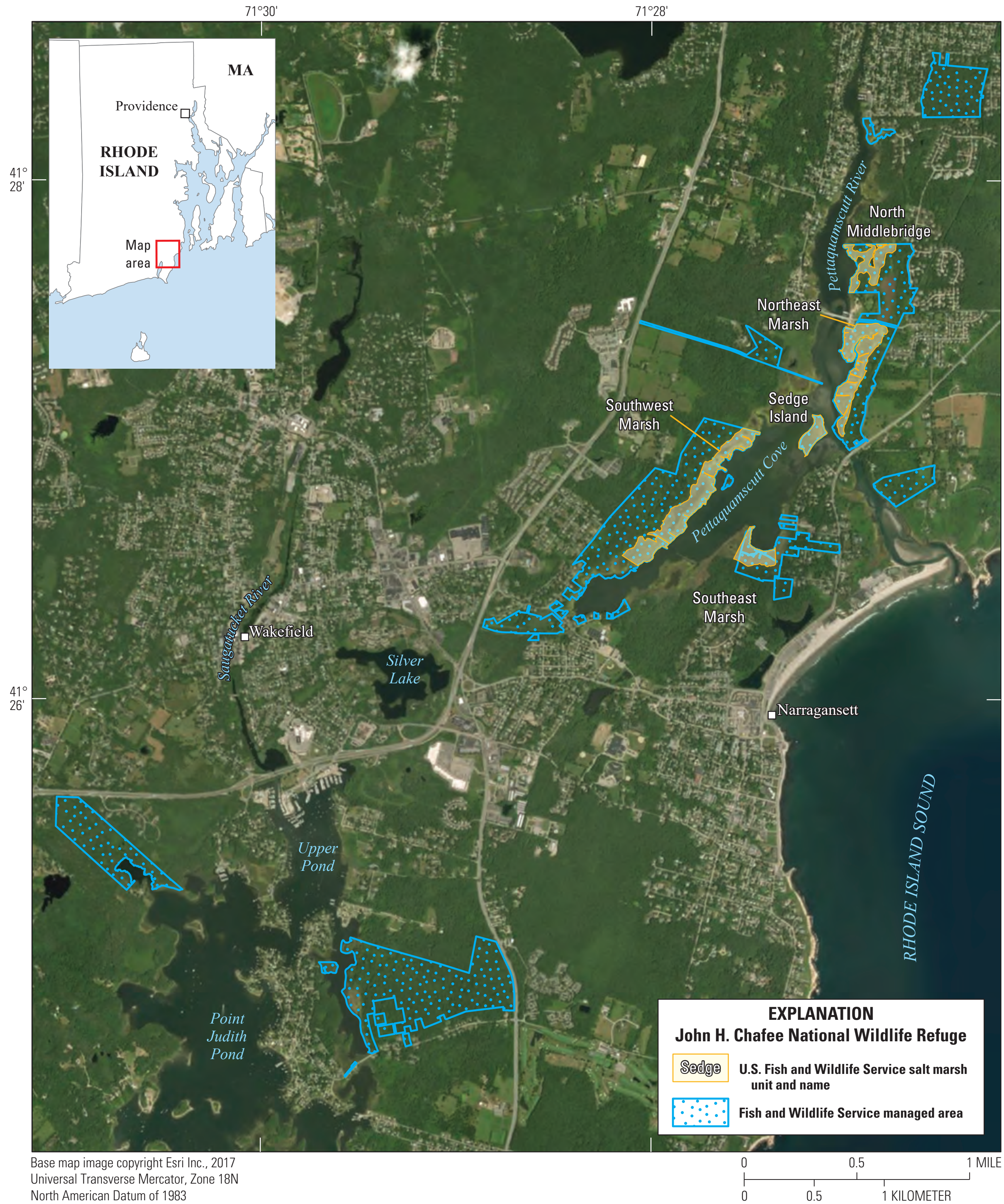


**Figure 2.** Salt marsh units at the John H. Chafee National Wildlife Refuge in Rhode Island.

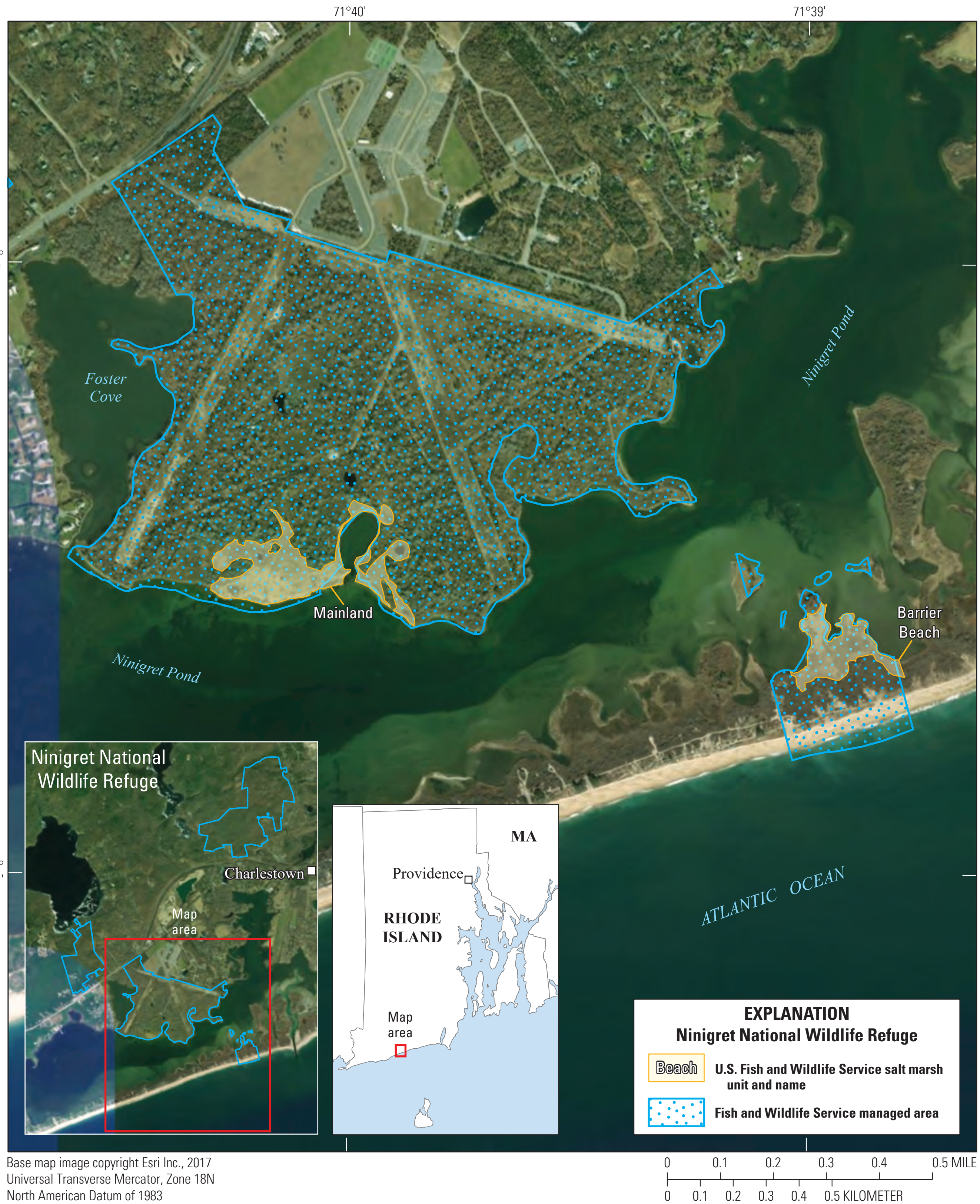


**Figure 3.** Salt marsh units at the Ninigret National Wildlife Refuge in Rhode Island.


**Figure 4.** Salt marsh units at the Sachuest Point National Wildlife Refuge in Rhode Island.

## 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. 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 while considering 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 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 (app. 1), 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 (app. 2). Neckles and others (2015) provided details regarding development of the structured decision-making framework and a case-study application to Prime Hook National Wildlife Refuge.

## Application to the Rhode Island National Wildlife Refuge Complex

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.

Participants identified a range of possible management actions for achieving objectives within each salt marsh unit at the Rhode Island National Wildlife Refuge Complex and estimated the total cost of implementation over 5 years. Potential actions to enhance salt marsh integrity ranged from focused efforts that restore natural hydrology, control *Phragmites*, or protect shorelines, to larger scale projects that alter marsh

**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 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 one. 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 amount of 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.

elevation or vegetation succession (table 3, in back of report). Invasive species occurred at low densities in only three salt marsh units and were predicted to have minimal influence on marsh vegetation; therefore, invasive control strategies were not considered in this prototype. 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. Baseline conditions were estimated by using expert judgment for three metrics that lacked assessment data (abundance of American black ducks, density of spiders, change in marsh surface elevation relative to sea-level rise). Regional influence diagrams relating management strategies to outcomes aided in predicting consequences of management actions (app. 1). 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 inherently included considerable uncertainty surrounding the complex interactions among controlling factors and salt marsh ecosystem components.

Following the workshop, the potential management benefit of each salt marsh integrity performance metric was calculated by converting salt marsh integrity metric scores (table 3, workshop output) to weighted utilities (table 4, in back of report), using regional value functions (app. 2). Weighted utilities were 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 used to find the management portfolio (the combination of actions, one action per salt marsh unit) that maximizes the total management benefit across all units under varying cost scenarios for

**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 |

the entire the refuge. Constrained optimization using integer linear programming was implemented in the Solver tool in Microsoft Excel (Kirkwood, 1997). Budget constraints were increased in $5,000 or $10,000 increments up to $50,000; in $50,000 increments up to $200,000; in $100,000 increments up to $1 million; in $500,000 increments up to $2 million; and in $1 million increments thereafter. The upper limit to potential costs was not determined in advance; rather, it reflected the total estimated costs of the proposed management actions. A cost-benefit plot of the portfolios identified through the optimization analysis 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). The cost-benefit plot also revealed the cost above which further expenditures would yield diminishing returns on investment. To exemplify use of the decision-making framework to understand how a given portfolio could affect specific management objectives, the refuge-scale management benefits for individual performance metrics were compared between one optimal portfolio and those predicted with no management action taken.

# Results of Constrained Optimization

Management actions identified to improve marsh integrity at the Rhode Island National Wildlife Refuge Complex included strategies to restore or enhance physical marsh features, restore hydrology, protect shorelines from erosion, promote use by migratory birds, reduce the spread of non-native vegetation, and manage native marsh vegetation (table 3). For costs ranging from $0 to $6.3 million (for implementing a combination of actions in Restored Marsh at the Sachuest Point National Wildlife Refuge), the estimated management benefits for individual actions across all metrics, measured as weighted utilities, ranged from 0.304 (for controlling *Phragmites* with herbicide in the Mainland management unit, Ninigret National Wildlife Refuge) to 0.960 (for implementing a combination of actions in the Sedge Island management unit, Sachuest Point National Wildlife Refuge) (tables 3 and 4). Within each unit, the action with both the lowest management benefit and lowest cost was generally the “no-action” option. However, implementing *Phragmites* control with herbicide, in the absence of any other management action, yielded a lower total management benefit than implementing no management actions (for example, in Southeast Marsh at the Chafee National Wildlife Refuge).

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 at the refuge scale increased by 58 percent, from 4.793 to 7.576 (table 5) out of a possible maximum of 9.0 (the maximum possible management benefit of 1.0 for any management action, summed across nine salt marsh units). Graphical analysis showed a fairly consistent increase in management benefit as costs increased to $150,000 (fig. 5, portfolio 7). As expenditures increased beyond the cost of portfolio 7, total management benefit continued to increase but at a lower rate, yielding diminishing returns on investment.

Several patterns emerged relative to management actions selected for yielding the best returns on investments within the optimal set of portfolios (portfolios 2 through 7; table 5). Digging runnels (small ditches on the marsh surface) to improve drainage, which was included within the suite of potential management actions for all management units except Sedge Island (table 3), was consistently included in the optimal portfolios. Within some management units, the optimal portfolios combined runnel construction with other management

**Table 5.** Actions included in various management portfolios to maximize the total management benefits subject to increasing cost constraints at the Rhode Island National Refuge Complex.

[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 refuge-wide cost constraint. The management actions constituting individual portfolios were selected using constrained optimization. The maximum possible total management benefit for the refuge is 9, derived as the maximum possible total management benefit of 1.0 for any management action within one management unit, summed across 9 units. NWR, National Wildlife Refuge; NA, no action]

| Portfolio | Salt marsh management unit | | | | | | | | | Total cost (dollars) | Total management benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Chafee NWR | | | | | Ninigret NWR | | Sachuest Point NWR | | | |
| | Northeast Marsh | Southeast Marsh | Southwest Marsh | Sedge Island | North Middlebridge | Barrier Beach | Mainland | Restored Marsh | North Marsh | | |
| 1 | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0 | 4.783 |
| 2 | D | C | A | NA | B | B | NA | NA | NA | 4,660 | 5.884 |
| 3 | D | C | A | NA | B | B | B | NA | B | 12,460 | 6.222 |
| 4 | D | C | A | NA | F | B | B | M | B | 23,010 | 6.439 |
| 5 | D | C | J | NA | F | B | B | M | B | 40,110 | 6.453 |
| 6 | D | C | J | D | A | B | B | M | B | 99,438 | 6.461 |
| 7 | D | C | A | B | F | B | B | B | B | 149,349 | 6.723 |
| 8 | D | B | J | B | F | B | B | M | B | 171,351 | 6.743 |
| 9 | D | C | J | B | F | B | B | M | E | 283,999 | 6.783 |
| 10 | D | C | J | B | F | G | B | M | B | 359,801 | 6.866 |
| 11 | D | F | J | B | F | B | B | M | B | 492,947 | 6.923 |
| 12 | D | C | J | B | D | C | B | M | B | 595,688 | 6.992 |
| 13 | D | F | J | B | F | G | B | M | B | 684,199 | 7.046 |
| 14 | D | F | J | B | A | G | B | M | E | 798,977 | 7.087 |
| 15 | D | C | A | B | D | G | B | D | B | 899,490 | 7.145 |
| 16 | D | F | J | B | F | C | B | K | B | 994,392 | 7.21 |
| 17 | D | F | J | I | D | G | B | K | E | 1,455,833 | 7.393 |
| 18 | D | F | J | B | D | G | D | K | C | 1,933,835 | 7.524 |
| 19 | I | F | J | B | D | G | D | K | C | 2,982,093 | 7.552 |
| 20 | H | F | G | F | D | G | D | K | C | 3,851,493 | 7.576 |

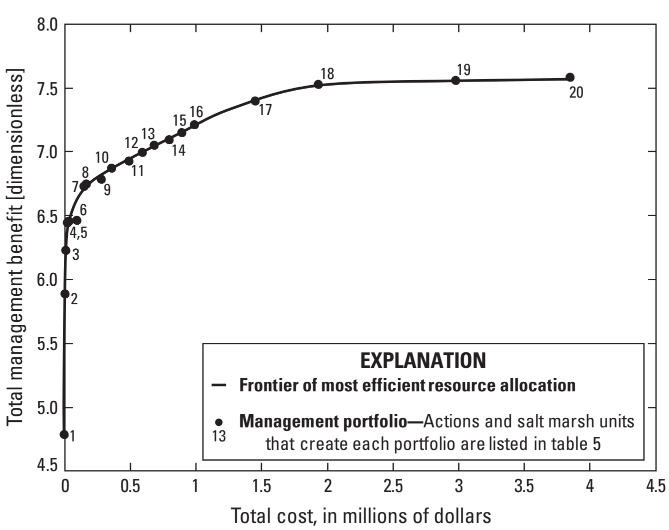


**Figure 5.** Predicted total management benefit of various portfolios, expressed as weighted utilities, relative to total annual cost at the Rhode Island National Wildlife Refuge Complex. Each portfolio (dot with number) represents a combination of nine management actions, one per salt marsh unit, as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

actions, such as construction of islands for tidal marsh obligate bird use (Southwest Marsh at the Chafee National Wildlife Refuge; Restored Marsh at the Sachuest Point National Wildlife Refuge) or *Phragmites* control (Southwest Marsh at the Chafee National Wildlife Refuge). Although performing thin layer deposition was a potential action for many management units, it was selected by an optimal portfolio under a total cost of $150,000 only for the Sedge Island unit at the Chafee National Wildlife Refuge. In other management units, thin layer deposition was either never selected (Northeast Marsh, North Middlebridge at the Chafee National Wildlife Refuge; North Marsh at the Sachuest Point National Wildlife Refuge) or included only in more costly portfolios. For example, thin layer deposition was included for Southeast Marsh, Chafee National Wildlife Refuge, in portfolio 11; for Barrier Beach, Ninigret National Wildlife Refuge, in portfolio 12; and in the Restored Marsh, Sachuest Point National Wildlife Refuge, in portfolio 15 (table 5). In contrast, some management actions were never included in an optimal portfolio. For example, although installation of living shorelines (shorelines that use plants or other natural elements to stabilize estuarine coasts, bays, or tributaries) was identified for reducing the effect of erosion on marsh edges within many management units, this action was never selected despite its relatively low cost.

Examination of the refuge-scale metric responses to actions included in portfolio 7, which is the turning point in the cost-benefit plot (fig. 5), revealed how implementation would affect specific management objectives. The actions included in portfolio 7 generated a prediction of modest gains in the overall management benefits derived from changes to the numbers of tidal marsh obligate birds and spiders (as an indicator of trophic health) and to flooding duration, and large gains in the capacity of marsh elevation to keep pace with sea-level rise (fig. 6). Ecologically, the combination of actions in this portfolio may result in an average 80-percent increase in tidal marsh obligate bird counts (averaged across all units), 666-percent increase in spider density, and 49-percent decrease in the deviation of surface flooding from the ideal reference condition (derived as the average difference between the predicted metric scores for the actions implemented in portfolio 7 and the “no-action” alternative; table 3). Implementation of actions in this portfolio was predicted to increase the capacity for marsh elevation to keep pace with sea-level rise in eight of the nine salt marsh units. The management benefits predicted for portfolios 2 through 6, at total costs considerably lower than portfolio 7, were derived primarily from expected improvements in the capacity for marsh elevation to keep pace with sea-level rise and from presumed increases in spider density and tidal marsh obligate birds (tables 3 and 4).

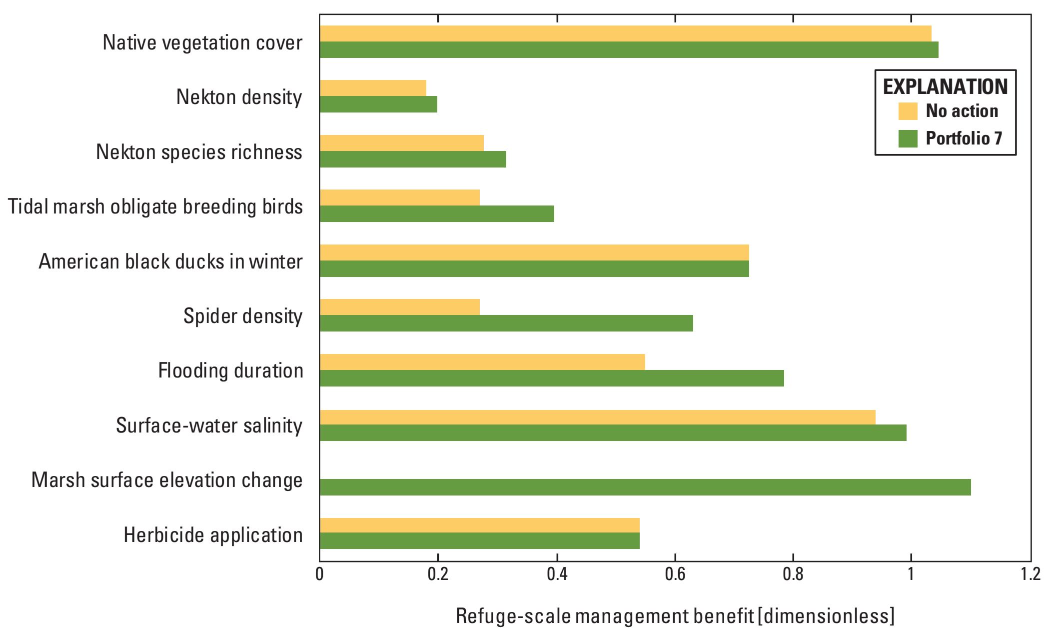


**Figure 6.** Predicted management benefit at the refuge scale for individual performance metrics, expressed as weighted utilities, resulting from implementation of the management actions included in portfolio 7, in comparison to the management benefit from the baseline “no-action” portfolio, at the Rhode Island National Wildlife Refuge Complex. Baseline (“no-action”) predicted management benefit for marsh surface elevation change is zero. The actions included in each portfolio are listed in table 5.

# Considerations for Optimizing Salt Marsh Management

A regional structured decision-making framework for salt marshes on 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 Rhode Island National Wildlife Refuge Complex. 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. Insights from this process may also be useful to inform future habitat management planning at the refuge.

The suite of potential management actions and predicted outcomes included in this prototype (table 3) were based on current understanding of the Rhode Island National Wildlife Refuge Complex salt marshes and hypothesized process-response pathways (app. 1). 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 may respond to accelerating rates of sea-level rise (Kirwan and Megonigal, 2013; Roman, 2017). In this prototype, digging runnels by hand or machine to improve drainage of the marsh surface was frequently projected to yield high management benefit for relatively low cost. Evaluating the responses of performance metrics to runnel creation is expected to help determine the conditions under which this technique improves marsh resilience. Future iterations of this decision model can incorporate improved understanding of runnel implementation costs and marsh response. 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 very coarse scale of measurement for change in marsh surface elevation relative to sea-level rise (table 1). Surface elevation tables (Lynch and others, 2015) were installed in North Marsh at the Sachuest Point National Wildlife Refuge in 2004 and in the other eight management units between 2011 and 2014 to obtain high-resolution measurements of change in marsh surface elevation (S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017). Incorporating this information into subsequent iterations of this structured decision-making framework would likely improve predictions related to the potential for marsh surface elevation to keep pace with sea-level rise.

Results of constrained optimizations (table 5) based on the objectives, management actions, and predicted outcomes included in this prototype identified four major areas in which to improve the utility of the prototype for refuge decision making. First, construction of islands as nesting habitat for tidal marsh obligate birds was rarely selected for implementation, suggesting that other methods focused directly on improving nest success might warrant investigation. Recent studies identify controlling predators within existing marshes (Roberts and others, 2017) and acquisition of adjacent parcels for marsh migration (Wiest and others, 2014) as approaches for limiting declines of saltmarsh sparrow populations. Second, although erosion of marsh edges is identified as a primary concern by refuge managers, establishing living shoreline to reduce wave action had minimal effect on the predicted total management benefit (Northeast, Southeast, and Southwest Marshes at the Chafee National Wildlife Refuge, table 5). This might lead managers to reconsider living shoreline as a management option at this refuge. Alternatively, deconstructing the objective of maintaining the extent of the marsh platform into subordinate objectives and performance metrics related to both horizontal and vertical gains and losses may help focus decision making on shoreline erosion. Third, the transparency of the structured decision-making framework reveals the tradeoffs associated with herbicide application for controlling *Phragmites*. Spread of *Phragmites* is a management concern at the Rhode Island National Wildlife Refuge Complex, and this prototype could be adapted to allow managers to evaluate the relative expected benefits and detriments of chemical and other control methods (table 3). Finally, the constrained optimizations analyzed in this report 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 Rhode Island National Wildlife Refuge Complex provides 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). This lends confidence to use of this framework for decision making; however, including probability distributions for each performance metric in the decision model could be a high priority for future prototypes. 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 Rhode Island National Wildlife Refuge Complex is based on a hierarchy of regional objectives and regional value functions relating performance metrics to perceived management benefits. It will be important to ensure that subsequent iterations reflect evolving management objectives and desired outcomes. 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.

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# Tables 3–4

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

[TLD, thin layer deposition; BMP, best management practice]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 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[2] (percent) | Surface-water salinity[2] (part per thousand) | | |
| Chafee—Northeast Marsh | | | | | | | | | | | |
| No action | 0 | 100 | 55.91 | 13 | 2.63 | High | 15 | 0.4 | 4 | 0 | 0 |
| A. Thin layer deposition/dredge source | 1,000,000 | 100 | 55.91 | 13 | 4.5 | High | 30 | 0 | 2 | 0.5 | 0 |
| B. Runnels dug by machine | 3,250 | 100 | 59.74 | 14 | 3 | High | 30 | 0.3 | 1 | 0.5 | 0 |
| C. Thin layer deposition plus planting of TLD area | 1,045,008 | 100 | 55.91 | 13 | 4.5 | High | 30 | 0.4 | 4 | 1 | 0 |
| D. Runnels dug by hand | 672 | 100 | 59.74 | 14 | 3 | High | 30 | 0.3 | 1 | 1 | 0 |
| E. Living shoreline (study, 600 feet, coir logs, oyster shell bags, labor) | 20,100 | 100 | 57.71 | 13.5 | 2.63 | High | 15 | 0.4 | 4 | 0 | 0 |
| F. Under road connection to cattail marsh (design, materials, build) | 120,000 | 100 | 59.74 | 14 | 2.63 | High | 15 | 0.4 | 4 | 0 | 0 |
| G. Floating islands (3) for tidal marsh obligate birds | 2,100 | 100 | 55.95 | 13 | 2.63 | High | 15 | 0.4 | 4 | 0 | 0 |
| H. B+C+D+E+F+G | 1,191,130 | 100 | 64.54 | 14 | 6 | High | 30 | 0 | 0 | 1 | 0 |
| I. B+C+D | 1,048,930 | 100 | 60.75 | 14 | 5.5 | High | 30 | 0 | 0 | 1 | 0 |
| J. B+D+E | 24,022 | 100 | 60.75 | 14 | 3 | High | 30 | 0.3 | 1 | 0.5 | 0 |
| K. B+D+G | 6,022 | 100 | 59.23 | 14 | 4.6 | High | 30 | 0.3 | 1 | 0.5 | 0 |
| L. B+D+F | 123,922 | 100 | 60.75 | 14 | 4.5 | High | 30 | 0.3 | 1 | 0.5 | 0 |
| Chafee—Southeast Marsh | | | | | | | | | | | |
| No action | 0 | 97 | 38 | 6 | 0 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| A. *Phragmites* control with herbicide | 7,035 | 100 | 40 | 7 | 1 | Medium | 1 | 64.87 | 6 | 0 | 1 |
| B. Runnels dug by machine | 3,250 | 98 | 45 | 8 | 3 | Medium | 15 | 13 | 3 | 0.5 | 0 |
| C. Runnels dug by hand | 448 | 98 | 45 | 8 | 3 | Medium | 15 | 13 | 3 | 0.5 | 0 |
| D. Marsh migration (tree girdling, staff time) | 1,000 | 97 | 38 | 6 | 0 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| E. Living shoreline | 20,100 | 97 | 40 | 7 | 0 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| F. Thin layer deposition plus planting of TLD area | 324,846 | 97 | 40 | 8 | 4.5 | Medium | 30 | 8 | 2 | 1 | 0 |

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

[TLD, thin layer deposition; BMP, best management practice]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics: Native vegetation (percent cover) | Nekton: Density (number of animals per square meter) | Nekton: Species richness (number) | Tidal marsh obligate birds (summed number per point) | American black ducks use[1] | Spider density (number per square meter) | Hydrology: Duration of surface flooding[2] (percent) | Hydrology: Surface-water salinity[2] (part per thousand) | Marsh surface elevation change relative to sea-level rise[3] | Herbicide application[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chafee—Southeast Marsh—Continued** | | | | | | | | | | | |
| G. Floating islands (3) for tidal marsh obligate birds | 2,100 | 97 | 38 | 6 | 1 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| H. Partial stonewall removal to facilitate hydrology and marsh | 600 | 97 | 38 | 8 | 0 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| I. Trestle removal (underwater at head of Pett Cove) | 45,000 | 97 | 45 | 8 | 0 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| J. Narragansett Parks stormwater BMP | 175,000 | 97 | 45 | 8 | 0 | Medium | 1 | 64.87 | 6 | 0 | 0 |
| K. A+B+C+D+E+F+G+H+I+J | 579,379 | 100 | 60 | 10 | 6 | Medium | 30 | 8 | 0 | 1 | 1 |
| L. A+B+C+E | 30,833 | 100 | 45 | 9 | 3 | Medium | 15 | 13 | 3 | 0.5 | 1 |
| M. A+B+C+F | 335,579 | 100 | 46 | 8 | 5 | Medium | 30 | 8 | 3 | 1 | 1 |
| N. B+C+F | 328,544 | 97 | 45 | 8 | 5 | Medium | 30 | 8 | 1 | 0.5 | 0 |
| O. B+C+D+E+H | 25,398 | 97 | 45 | 8 | 3 | Medium | 15 | 13 | 3 | 0.5 | 0 |
| P. B+C+I | 48,698 | 97 | 45 | 8 | 3 | Medium | 15 | 13 | 3 | 0.5 | 0 |
| Q. B+C+J | 178,698 | 97 | 45 | 9 | 3 | Medium | 15 | 13 | 3 | 0.5 | 0 |
| **Chafee—Southwest Marsh** | | | | | | | | | | | |
| No action | 0 | 99 | 154.39 | 9 | 1.33 | High | 1 | 48 | 1 | 0 | 0 |
| A. Runnels dug by hand | 1,568 | 99 | 160 | 12 | 3 | High | 15 | 28 | 0 | 0.5 | 0 |
| B. Floating islands (3) for tidal marsh obligate birds | 2,100 | 99 | 154.39 | 9 | 1.5 | High | 1 | 48 | 1 | 0 | 0 |
| C. Living shoreline | 53,600 | 99 | 160 | 10 | 1.33 | High | 1 | 48 | 1 | 0 | 0 |
| D. Mumford Brook culvert upgrade | 120,000 | 99 | 154.39 | 9 | 1.33 | High | 1 | 48 | 1 | 0 | 0 |
| E. Mumford Brook stormwater BMP | 175,000 | 99 | 155 | 9 | 1.33 | High | 1 | 48 | 3 | 0 | 0 |
| F. *Phragmites* control (multiple sharp cut), no herbicide | 15,000 | 100 | 156 | 10 | 2 | High | 1 | 48 | 1 | 0 | 0 |
| G. A+B+C+D+E+F | 367,268 | 100 | 165 | 14 | 4.5 | High | 15 | 28 | 0 | 0.5 | 0 |
| H. A+B+C+D | 177,268 | 99 | 162 | 12 | 4 | High | 15 | 28 | 0 | 0.5 | 0 |

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

[TLD, thin layer deposition; BMP, best management practice]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 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[2] (percent) | Surface-water salinity[2] (part per thousand) | | |
| Chafee—Southwest Marsh—Continued | | | | | | | | | | | |
| I. A+B+C | 57,268 | 99 | 161 | 11 | 4 | High | 15 | 28 | 0 | 0.5 | 0 |
| J. A+B+F | 18,668 | 100 | 161 | 11 | 4.5 | High | 15 | 28 | 0 | 0.5 | 0 |
| K. A+F | 16,568 | 100 | 161 | 11 | 4 | High | 15 | 28 | 0 | 0.5 | 0 |
| L. D+E | 295,000 | 99 | 158 | 10 | 1.33 | High | 1 | 48 | 3 | 0 | 0 |
| M. A+C | 55,168 | 99 | 161 | 11 | 3 | High | 15 | 28 | 0 | 0.5 | 0 |
| Chafee—Sedge Island | | | | | | | | | | | |
| No action | 0 | 100 | 70.44 | 14 | 4.5 | High | 15 | 11.31 | 6 | 0 | 0 |
| A. Living shoreline | 53,600 | 100 | 71.62 | 14 | 4.5 | High | 15 | 11.31 | 6 | 0 | 0 |
| B. Thin layer deposition plus planting of TLD area | 128,439 | 100 | 82.36 | 14 | 6 | High | 30 | 6 | 3 | 1 | 0 |
| C. New low-marsh creation | 240,000 | 100 | 80.57 | 14 | 5 | High | 15 | 11.31 | 6 | 0 | 0 |
| D. Armor Sedge Island rock/soil/salt marsh mix | 60,000 | 100 | 80.57 | 14 | 5 | High | 15 | 11.31 | 6 | 0 | 0 |
| E. Shed removal/create salt marsh | 25,000 | 100 | 71.62 | 14 | 5 | High | 15 | 11.31 | 6 | 0 | 0 |
| F. A+B+C+D+E | 507,039 | 100 | 89.53 | 14 | 6.5 | High | 30 | 6 | 3 | 1 | 0 |
| G. A+B+C+D | 482,039 | 100 | 89.53 | 14 | 6 | High | 30 | 6 | 3 | 1 | 0 |
| H. A+B+C | 422,039 | 100 | 85.05 | 14 | 6 | High | 30 | 6 | 3 | 1 | 0 |
| I. B+D+E | 213,439 | 100 | 82.37 | 14 | 6 | High | 30 | 6 | 3 | 1 | 0 |
| J. A+D+E | 138,600 | 100 | 83.26 | 14 | 5 | High | 15 | 11.31 | 6 | 0 | 0 |
| Chafee—North Middlebridge | | | | | | | | | | | |
| No action | 0 | 99.5 | 19.95 | 10 | 0.93 | High | 15 | 2.99 | 1 | 0 | 0 |
| A. Runnels dug by machine | 3,900 | 99.5 | 25 | 11 | 2 | High | 30 | 1 | 0.5 | 0.5 | 0 |
| B. Runnels dug by hand | 672 | 99.5 | 25 | 11 | 2 | High | 15 | 1 | 0.5 | 0.5 | 0 |
| C. Thin layer deposition | 240,000 | 99.5 | 21 | 10 | 3 | High | 30 | 0 | 0 | 1 | 0 |
| D. A+B+E | 253,011 | 99.5 | 30 | 11 | 4 | High | 30 | 0 | 0 | 1 | 0 |

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

[TLD, thin layer deposition; BMP, best management practice]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 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[2] (percent) | Surface-water salinity[2] (part per thousand) | | |
| **Chafee—North Middlebridge—Continued** | | | | | | | | | | | |
| E. Thin layer deposition plus planting of TLD area | 248,439 | 99.5 | 21 | 10 | 3 | High | 30 | 0 | 0 | 1 | 0 |
| F. A+B | 4,572 | 99.5 | 25 | 11 | 2 | High | 30 | 1 | 0.5 | 0.5 | 0 |
| **Ninigret—Barrier Beach** | | | | | | | | | | | |
| No action | 0 | 99.5 | 33.30 | 7 | 4.55 | Medium | 30 | 9 | 17 | 0 | 0 |
| A. *Phragmites* control with herbicide | 4,690 | 100 | 35.26 | 8 | 5 | Medium | 30 | 9 | 17 | 0 | 1 |
| B. Runnels dug by machine | 1,300 | 100 | 41.14 | 9 | 5 | Medium | 30 | 7 | 9 | 0.5 | 0 |
| C. Thin layer deposition: mechanical, trucked in and spread | 180,000 | 99.5 | 34.28 | 8 | 6 | Medium | 30 | 6 | 4 | 1 | 0 |
| D. Thin layer deposition plus planting of TLD area | 191,252 | 99.5 | 44.07 | 8 | 6 | Medium | 30 | 6 | 4 | 1 | 0 |
| E. A+B | 5,990 | 100 | 42.11 | 10 | 5.5 | Medium | 30 | 7 | 9 | 0.5 | 1 |
| F. A+D | 195,942 | 100 | 36.24 | 9 | 6 | Medium | 30 | 6 | 4 | 1 | 1 |
| G. B+D | 192,552 | 99.5 | 47.01 | 9 | 6 | Medium | 30 | 5 | 0 | 1 | 0 |
| **Ninigret—Mainland** | | | | | | | | | | | |
| No action | 0 | 45.33 | 23.22 | 9 | 1.48 | Low | 1 | 99 | 3 | 0 | 0 |
| A. *Phragmites* control with herbicide | 23,450 | 100 | 24.89 | 9 | 3 | Low | 1 | 99 | 3 | 0 | 1 |
| B. Runnels dug by machine | 3,250 | 55 | 26.88 | 10 | 2.5 | Low | 15 | 39 | 0 | 0 | 0 |
| C. Removing contaminants, creating 3 acres of high marsh | 200,000 | 60 | 24.89 | 9 | 4 | Low | 1 | 99 | 3 | 0 | 0 |
| D. Remove contaminants and planting contaminant area with salt marsh grass | 211,252 | 100 | 24.89 | 9 | 4 | Low | 15 | 99 | 3 | 0 | 0 |
| E. A+B | 26,700 | 100 | 28.88 | 10 | 4 | Low | 15 | 39 | 0 | 0 | 1 |
| F. A+C | 223,450 | 100 | 24.89 | 9 | 4 | Low | 1 | 99 | 3 | 0 | 1 |
| G. B+C | 203,250 | 75 | 28.88 | 10 | 3 | Low | 15 | 39 | 0 | 0 | 0 |
| H. A+B+D | 237,952 | 100 | 28.88 | 10 | 5 | Low | 15 | 39 | 0 | 0 | 1 |

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

[TLD, thin layer deposition; BMP, best management practice]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 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[2] (percent) | Surface-water salinity[2] (part per thousand) | | |
| **Sachuest Point—Restored Marsh** | | | | | | | | | | | |
| No action | 0 | 93 | 44.16 | 11 | 2.16 | High | 1 | 0.51 | 1 | 0 | 0 |
| A. *Phragmites* control with herbicide | 46,900 | 100 | 44.67 | 11 | 4 | High | 15 | 0.51 | 1 | 0 | 1 |
| B. Runnels dug by machine | 4,550 | 94 | 48.32 | 11 | 3 | High | 15 | 0.3 | 0.5 | 0.5 | 0 |
| C. Remove landfill, create 11 acres high marsh, plant landfill area | 5,904,943 | 94 | 44.67 | 11 | 5 | High | 30 | 0 | 0 | 1 | 0 |
| D. Thin layer deposition: mechanical, trucked in and spread | 315,000 | 93 | 44.67 | 11 | 4 | High | 30 | 0 | 0 | 1 | 0 |
| E. Thin layer deposition plus planting of TLD area | 324,846 | 93 | 44.67 | 11 | 4 | High | 30 | 0.51 | 1 | 1 | 0 |
| F. Floating islands (3) for tidal marsh obligate birds | 2,100 | 93 | 44.16 | 11 | 2.5 | High | 1 | 0.51 | 1 | 0 | 0 |
| G. Remove landfill and create 11 acres of high marsh | 5,874,000 | 93 | 44.67 | 11 | 5 | High | 30 | 0 | 0 | 1 | 0 |
| H. A+B+C+E+F | 6,283,339 | 100 | 50.14 | 11 | 6.5 | High | 30 | 0 | 0 | 1 | 1 |
| I. A+B | 51,450 | 100 | 48.32 | 11 | 4.5 | High | 15 | 0.3 | 0.5 | 0.5 | 1 |
| J. A+B+E | 376,296 | 100 | 48.32 | 11 | 5.5 | High | 30 | 0 | 0 | 1 | 1 |
| K. B+E | 329,396 | 94 | 48.32 | 11 | 5 | High | 30 | 0 | 0 | 1 | 0 |
| L. A+F | 49,000 | 100 | 44.67 | 11 | 4.5 | High | 15 | 0.3 | 1 | 0 | 1 |
| M. B+F | 6,650 | 94 | 48.32 | 11 | 3.5 | High | 15 | 0.3 | 0.5 | 0.5 | 0 |
| **Sachuest Point—North Marsh** | | | | | | | | | | | |
| No action | 0 | 90.33 | 25.01 | 7 | 6.68 | Medium | 15 | 39.06 | 3 | 0 | 0 |
| A. *Phragmites* control with herbicide | 9,380 | 100 | 26.61 | 8 | 7 | Medium | 15 | 39.06 | 3 | 0 | 1 |
| B. Runnels dug by machine | 4,550 | 93 | 29.56 | 9 | 8 | Medium | 30 | 16 | 1 | 0.5 | 0 |
| C. Replace culverts with water control structure, connector road | 475,000 | 94 | 29.56 | 11 | 8 | Medium | 30 | 11 | 0 | 1 | 0 |
| D. Thin layer deposition plus planting of TLD area | 324,846 | 90.33 | 25.62 | 7 | 8 | Medium | 30 | 3 | 0 | 1 | 0 |
| E. Reconfigure channels | 120,000 | 90.33 | 24.91 | 7 | 6.68 | Medium | 15 | 16 | 1 | 1 | 0 |

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

[TLD, thin layer deposition; BMP, best management practice]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 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[2] (percent) | Surface-water salinity[2] (part per thousand) | | |
| Sachuest Point—North Marsh—Continued | | | | | | | | | | | |
| F. Maidford crossing structure | 475,000 | 94 | 30.55 | 8 | 6.68 | Medium | 30 | 6 | 1 | 1 | 0 |
| G. A+B+C+D+E+F | 1,408,776 | 100 | 34.49 | 11 | 9 | Medium | 30 | 1 | 0 | 1 | 1 |
| H. A+B+C+D+E | 933,776 | 100 | 33.50 | 11 | 8.5 | Medium | 30 | 1.5 | 0.5 | 1 | 1 |
| I. A+B+C+D | 813,776 | 100 | 32.52 | 11 | 8.5 | Medium | 30 | 2.5 | 1.5 | 1 | 1 |
| J. A+B+C | 488,930 | 100 | 32.52 | 10 | 8 | Medium | 30 | 2 | 1 | 0.5 | 1 |
| K. A+B | 13,930 | 100 | 29.56 | 11 | 8 | Medium | 30 | 16 | 2 | 0.5 | 1 |
| L. B+E | 124,550 | 93 | 30.55 | 10 | 8 | Medium | 30 | 16 | 1.5 | 0.5 | 0 |
| M. B+F | 479,550 | 93 | 31.53 | 10 | 8 | Medium | 30 | 4 | 1.5 | 0.5 | 0 |
| N. B+E+F | 599,550 | 93 | 31.53 | 11 | 8 | Medium | 30 | 3 | 1 | 0.5 | 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, lower than sea-level rise; 1, above sea-level rise; 0.5, intermediate.

[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 management units at the Rhode Island National Wildlife Refuge Complex.

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). 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 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics. TLD, thin layer deposition; BMP, best management practice]

| Management action | Performance metrics | | | | | | | | | | 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 | | | |
| Chafee—Northeast Marsh | | | | | | | | | | | |
| No action | 0.120 | 0.023 | 0.042 | 0.029 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0.06 | 0.639 |
| A. Thin layer deposition/ dredge source | 0.120 | 0.023 | 0.042 | 0.050 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.815 |
| B. Runnels dug by machine | 0.120 | 0.025 | 0.045 | 0.033 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.803 |
| C. Thin layer deposition plus planting of TLD area | 0.120 | 0.023 | 0.042 | 0.050 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.925 |
| D. Runnels dug by hand | 0.120 | 0.025 | 0.045 | 0.033 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.913 |
| E. Living shoreline (study, 600 feet, coir logs, oyster shell bags, labor) | 0.120 | 0.024 | 0.043 | 0.029 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0.06 | 0.642 |
| F. Under road connection to cattail marsh (design, materials, build) | 0.120 | 0.025 | 0.045 | 0.029 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0.06 | 0.644 |
| G. Floating islands (3) for tidal marsh obligate birds | 0.120 | 0.023 | 0.042 | 0.029 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0.06 | 0.639 |
| H. B+C+D+E+F+G | 0.120 | 0.026 | 0.045 | 0.067 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.948 |
| I. B+C+D | 0.120 | 0.025 | 0.045 | 0.061 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.941 |
| J. B+D+E | 0.120 | 0.025 | 0.045 | 0.033 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.803 |
| K. B+D+G | 0.120 | 0.024 | 0.045 | 0.051 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.821 |
| L. B+D+F | 0.120 | 0.025 | 0.045 | 0.050 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.820 |
| Chafee—Southeast Marsh | | | | | | | | | | | |
| No action | 0.119 | 0.017 | 0.019 | 0.000 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.400 |
| A. *Phragmites* control with herbicide | 0.120 | 0.018 | 0.023 | 0.011 | 0.075 | 0 | 0 | 0.11 | 0 | 0 | 0.357 |
| B. Runnels dug by machine | 0.119 | 0.020 | 0.026 | 0.033 | 0.075 | 0.045 | 0.099 | 0.11 | 0.11 | 0.06 | 0.697 |
| C. Runnels dug by hand | 0.119 | 0.020 | 0.026 | 0.033 | 0.075 | 0.045 | 0.099 | 0.11 | 0.11 | 0.06 | 0.697 |
| D. Marsh migration (tree girdling, staff time) | 0.119 | 0.017 | 0.019 | 0.000 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.400 |
| E. Living shoreline | 0.119 | 0.018 | 0.023 | 0.000 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.404 |
| F. Thin layer deposition plus planting of TLD area | 0.119 | 0.018 | 0.026 | 0.050 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.878 |
| G. Floating islands (3) for tidal marsh obligate birds | 0.119 | 0.017 | 0.019 | 0.011 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.411 |

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh management units at the Rhode Island National Wildlife Refuge Complex.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). 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 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics. TLD, thin layer deposition; BMP, best management practice]

| Management action | Performance metrics | | | | | | | | | | 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 | | | |
| **Chafee—Southeast Marsh—Continued** | | | | | | | | | | | |
| H. Partial stonewall removal to facilitate hydrology and marsh | 0.119 | 0.017 | 0.026 | 0.000 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.407 |
| I. Trestle removal (underwater at head of Pett Cove) | 0.119 | 0.020 | 0.026 | 0.000 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.409 |
| J. Narragansett Parks stormwater BMP | 0.119 | 0.020 | 0.026 | 0.000 | 0.075 | 0 | 0 | 0.11 | 0 | 0.06 | 0.409 |
| K. A+B+C+D+E+F+G+H+I+J | 0.120 | 0.025 | 0.032 | 0.067 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.849 |
| L. A+B+C+E | 0.120 | 0.020 | 0.029 | 0.033 | 0.075 | 0.045 | 0.099 | 0.11 | 0.11 | 0 | 0.641 |
| M. A+B+C+F | 0.120 | 0.020 | 0.026 | 0.056 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.826 |
| N. B+C+F | 0.119 | 0.020 | 0.026 | 0.056 | 0.075 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.775 |
| O. B+C+D+E+H | 0.119 | 0.020 | 0.026 | 0.033 | 0.075 | 0.045 | 0.099 | 0.11 | 0.11 | 0.06 | 0.697 |
| P. B+C+I | 0.119 | 0.020 | 0.026 | 0.033 | 0.075 | 0.045 | 0.099 | 0.11 | 0.11 | 0.06 | 0.697 |
| Q. B+C+J | 0.119 | 0.020 | 0.029 | 0.033 | 0.075 | 0.045 | 0.099 | 0.11 | 0.11 | 0.06 | 0.700 |
| **Chafee—Southwest Marsh** | | | | | | | | | | | |
| No action | 0.120 | 0.044 | 0.029 | 0.015 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.477 |
| A. Runnels dug by hand | 0.120 | 0.044 | 0.039 | 0.033 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.705 |
| B. Floating islands (3) for tidal marsh obligate birds | 0.120 | 0.044 | 0.029 | 0.017 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.479 |
| C. Living shoreline | 0.120 | 0.044 | 0.032 | 0.015 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.481 |
| D. Mumford Brook culvert upgrade | 0.120 | 0.044 | 0.029 | 0.015 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.477 |
| E. Mumford Brook stormwater BMP | 0.120 | 0.044 | 0.029 | 0.015 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.477 |
| F. *Phragmites* control (multiple sharp cut), no herbicide | 0.120 | 0.044 | 0.032 | 0.022 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.488 |
| G. A+B+C+D+E+F | 0.120 | 0.045 | 0.045 | 0.050 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.729 |
| H. A+B+C+D | 0.120 | 0.045 | 0.039 | 0.044 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.716 |
| I. A+B+C | 0.120 | 0.045 | 0.035 | 0.044 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.713 |
| J. A+B+F | 0.120 | 0.045 | 0.035 | 0.050 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.719 |
| K. A+F | 0.120 | 0.045 | 0.035 | 0.044 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.713 |
| L. D+E | 0.120 | 0.044 | 0.032 | 0.015 | 0.1 | 0 | 0 | 0.11 | 0 | 0.06 | 0.481 |
| M. A+C | 0.120 | 0.045 | 0.035 | 0.033 | 0.1 | 0.045 | 0.044 | 0.11 | 0.11 | 0.06 | 0.702 |

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh management units at the Rhode Island National Wildlife Refuge Complex.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). 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 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics. TLD, thin layer deposition; BMP, best management practice]

| Management action | Performance metrics | | | | | | | | | | 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 | | | |
| **Chafee—Sedge Island** | | | | | | | | | | | |
| No action | 0.120 | 0.028 | 0.045 | 0.050 | 0.1 | 0.045 | 0.105 | 0.11 | 0 | 0.06 | 0.663 |
| A. Living shoreline | 0.120 | 0.028 | 0.045 | 0.050 | 0.1 | 0.045 | 0.105 | 0.11 | 0 | 0.06 | 0.663 |
| B. Thin layer deposition plus planting of TLD area | 0.120 | 0.031 | 0.045 | 0.067 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.953 |
| C. New low-marsh creation | 0.120 | 0.030 | 0.045 | 0.056 | 0.1 | 0.045 | 0.105 | 0.11 | 0 | 0.06 | 0.671 |
| D. Armor Sedge Island rock/soil/salt marsh mix | 0.120 | 0.030 | 0.045 | 0.056 | 0.1 | 0.045 | 0.105 | 0.11 | 0 | 0.06 | 0.671 |
| E. Shed removal/create salt marsh | 0.120 | 0.028 | 0.045 | 0.056 | 0.1 | 0.045 | 0.105 | 0.11 | 0 | 0.06 | 0.669 |
| F. A+B+C+D+E | 0.120 | 0.033 | 0.045 | 0.072 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.960 |
| G. A+B+C+D | 0.120 | 0.033 | 0.045 | 0.067 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.954 |
| H. A+B+C | 0.120 | 0.032 | 0.045 | 0.067 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.953 |
| I. B+D+E | 0.120 | 0.031 | 0.045 | 0.067 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.953 |
| J. A+D+E | 0.120 | 0.031 | 0.045 | 0.056 | 0.1 | 0.045 | 0.105 | 0.11 | 0 | 0.06 | 0.672 |
| **Chafee—North Middlebridge** | | | | | | | | | | | |
| No action | 0.120 | 0.010 | 0.032 | 0.010 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0.06 | 0.597 |
| A. Runnels dug by machine | 0.120 | 0.012 | 0.035 | 0.022 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.769 |
| B. Runnels dug by hand | 0.120 | 0.012 | 0.035 | 0.022 | 0.1 | 0.045 | 0.11 | 0.11 | 0.11 | 0.06 | 0.724 |
| C. Thin layer deposition | 0.120 | 0.010 | 0.032 | 0.033 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.886 |
| D. A+B+E | 0.120 | 0.014 | 0.035 | 0.044 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.904 |
| E. Thin layer deposition plus planting of TLD area | 0.120 | 0.010 | 0.032 | 0.033 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.886 |
| F. A+B | 0.120 | 0.012 | 0.035 | 0.022 | 0.1 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.769 |
| **Ninigret—Barrier Beach** | | | | | | | | | | | |
| No action | 0.120 | 0.015 | 0.023 | 0.051 | 0.075 | 0.09 | 0.11 | 0.059 | 0 | 0.06 | 0.602 |
| A. *Phragmites* control with herbicide | 0.120 | 0.016 | 0.026 | 0.056 | 0.075 | 0.09 | 0.11 | 0.059 | 0 | 0 | 0.551 |
| B. Runnels dug by machine | 0.120 | 0.018 | 0.029 | 0.056 | 0.075 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.778 |
| C. Thin layer deposition: mechanical, trucked in and spread | 0.120 | 0.016 | 0.026 | 0.067 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.893 |
| D. Thin layer deposition plus planting of TLD area | 0.120 | 0.019 | 0.026 | 0.067 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.897 |

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh management units at the Rhode Island National Wildlife Refuge Complex.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). 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 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics. TLD, thin layer deposition; BMP, best management practice]

| Management action | Performance metrics | | | | | | | | | | 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 | | | |
| **Ninigret—Barrier Beach—Continued** | | | | | | | | | | | |
| E. A+B | 0.120 | 0.019 | 0.032 | 0.061 | 0.075 | 0.09 | 0.11 | 0.11 | 0.11 | 0 | 0.727 |
| F. A+D | 0.120 | 0.017 | 0.029 | 0.067 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.837 |
| G. B+D | 0.120 | 0.021 | 0.029 | 0.067 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.901 |
| **Ninigret—Mainland** | | | | | | | | | | | |
| No action | 0.083 | 0.011 | 0.029 | 0.016 | 0 | 0 | 0 | 0.11 | 0 | 0.06 | 0.309 |
| A. *Phragmites* control with herbicide | 0.120 | 0.012 | 0.029 | 0.033 | 0 | 0 | 0 | 0.11 | 0 | 0 | 0.304 |
| B. Runnels dug by machine | 0.093 | 0.013 | 0.032 | 0.028 | 0 | 0.045 | 0.004 | 0.11 | 0 | 0.06 | 0.384 |
| C. Removing contaminants, creating 3 acres of high marsh | 0.097 | 0.012 | 0.029 | 0.044 | 0 | 0 | 0 | 0.11 | 0 | 0.06 | 0.352 |
| D. Remove contaminants and planting contaminant area with salt marsh grass | 0.120 | 0.012 | 0.029 | 0.044 | 0 | 0.045 | 0 | 0.11 | 0 | 0.06 | 0.420 |
| E. A+B | 0.120 | 0.014 | 0.032 | 0.044 | 0 | 0.045 | 0.004 | 0.11 | 0 | 0 | 0.369 |
| F. A+C | 0.120 | 0.012 | 0.029 | 0.044 | 0 | 0 | 0 | 0.11 | 0 | 0 | 0.315 |
| G. B+C | 0.108 | 0.014 | 0.032 | 0.033 | 0 | 0.045 | 0.004 | 0.11 | 0 | 0.06 | 0.406 |
| H. A+B+D | 0.120 | 0.014 | 0.032 | 0.056 | 0 | 0.045 | 0.004 | 0.11 | 0 | 0 | 0.380 |
| **Sachuest Point—Restored Marsh** | | | | | | | | | | | |
| No action | 0.117 | 0.020 | 0.035 | 0.024 | 0.1 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.576 |
| A. *Phragmites* control with herbicide | 0.120 | 0.020 | 0.035 | 0.044 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0 | 0.584 |
| B. Runnels dug by machine | 0.118 | 0.021 | 0.035 | 0.033 | 0.1 | 0.045 | 0.11 | 0.11 | 0.11 | 0.06 | 0.742 |
| C. Remove landfill, create 11 acres high marsh, plant landfill area | 0.118 | 0.020 | 0.035 | 0.056 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.918 |
| D. Thin layer deposition: mechanical, trucked in and spread | 0.117 | 0.020 | 0.035 | 0.044 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.907 |
| E. Thin layer deposition plus planting of TLD area | 0.117 | 0.020 | 0.035 | 0.044 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.907 |
| F. Floating islands (3) for tidal marsh obligate birds | 0.117 | 0.020 | 0.035 | 0.028 | 0.1 | 0 | 0.11 | 0.11 | 0 | 0.06 | 0.580 |
| G. Remove landfill and create 11 acres of high marsh | 0.117 | 0.020 | 0.035 | 0.056 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.918 |
| H. A+B+C+E+F | 0.120 | 0.022 | 0.035 | 0.072 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.879 |

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within salt marsh management units at the Rhode Island National Wildlife Refuge Complex.—Continued

[Numeric table entries are weighted utilities, which were calculated as raw utilities multiplied by objective weights. Unitless raw utilities were derived from metric scores (table 3) using existing regional value functions (app. 2). 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 1). The total management benefit for each action is the sum of weighted utilities across all performance metrics. TLD, thin layer deposition; BMP, best management practice]

| Management action | Performance metrics | | | | | | | | | | 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 | | | |
| **Sachuest Point—Restored Marsh—Continued** | | | | | | | | | | | |
| I. A+B | 0.120 | 0.021 | 0.035 | 0.050 | 0.1 | 0.045 | 0.11 | 0.11 | 0.11 | 0 | 0.701 |
| J. A+B+E | 0.120 | 0.021 | 0.035 | 0.061 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.867 |
| K. B+E | 0.118 | 0.021 | 0.035 | 0.056 | 0.1 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.919 |
| L. A+F | 0.120 | 0.020 | 0.035 | 0.050 | 0.1 | 0.045 | 0.11 | 0.11 | 0 | 0 | 0.590 |
| M. B+F | 0.118 | 0.021 | 0.035 | 0.039 | 0.1 | 0.045 | 0.11 | 0.11 | 0.11 | 0.06 | 0.748 |
| **Sachuest Point—North Marsh** | | | | | | | | | | | |
| No action | 0.116 | 0.012 | 0.023 | 0.074 | 0.075 | 0.045 | 0.003 | 0.11 | 0 | 0.06 | 0.518 |
| A. *Phragmites* control with herbicide | 0.120 | 0.013 | 0.026 | 0.078 | 0.075 | 0.045 | 0.003 | 0.11 | 0 | 0 | 0.470 |
| B. Runnels dug by machine | 0.117 | 0.014 | 0.029 | 0.089 | 0.075 | 0.09 | 0.088 | 0.11 | 0.11 | 0.06 | 0.782 |
| C. Replace culverts with water control structure, connector road | 0.118 | 0.014 | 0.035 | 0.089 | 0.075 | 0.09 | 0.106 | 0.11 | 0.22 | 0.06 | 0.917 |
| D. Thin layer deposition plus planting of TLD area | 0.116 | 0.012 | 0.023 | 0.089 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.905 |
| E. Reconfigure channels | 0.116 | 0.012 | 0.023 | 0.074 | 0.075 | 0.045 | 0.088 | 0.11 | 0.22 | 0.06 | 0.823 |
| F. Maidford crossing structure | 0.118 | 0.014 | 0.026 | 0.074 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0.06 | 0.897 |
| G. A+B+C+D+E+F | 0.120 | 0.016 | 0.035 | 0.100 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.876 |
| H. A+B+C+D+E | 0.120 | 0.016 | 0.035 | 0.094 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.870 |
| I. A+B+C+D | 0.120 | 0.015 | 0.035 | 0.094 | 0.075 | 0.09 | 0.11 | 0.11 | 0.22 | 0 | 0.870 |
| J. A+B+C | 0.120 | 0.015 | 0.032 | 0.089 | 0.075 | 0.09 | 0.11 | 0.11 | 0.11 | 0 | 0.751 |
| K. A+B | 0.120 | 0.014 | 0.035 | 0.089 | 0.075 | 0.09 | 0.088 | 0.11 | 0.11 | 0 | 0.731 |
| L. B+E | 0.117 | 0.014 | 0.032 | 0.089 | 0.075 | 0.09 | 0.088 | 0.11 | 0.11 | 0.06 | 0.786 |
| M. B+F | 0.117 | 0.015 | 0.032 | 0.089 | 0.075 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.808 |
| N. B+E+F | 0.117 | 0.015 | 0.035 | 0.089 | 0.075 | 0.09 | 0.11 | 0.11 | 0.11 | 0.06 | 0.811 |

# Appendixes 1–2

# Appendix 1. Regional Influence Diagrams

The influence diagrams (following the style of prototype diagrams in Neckles and others, 2015) in this appendix (figs. 1.1–1.8) relate possible management strategies to performance metrics. Shapes represent elements of decisions, as follows: rectangles for actions, rectangles with rounded corners for deterministic factors, ovals for stochastic events, and hexagons for consequences expressed as a performance metric.

## 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.]

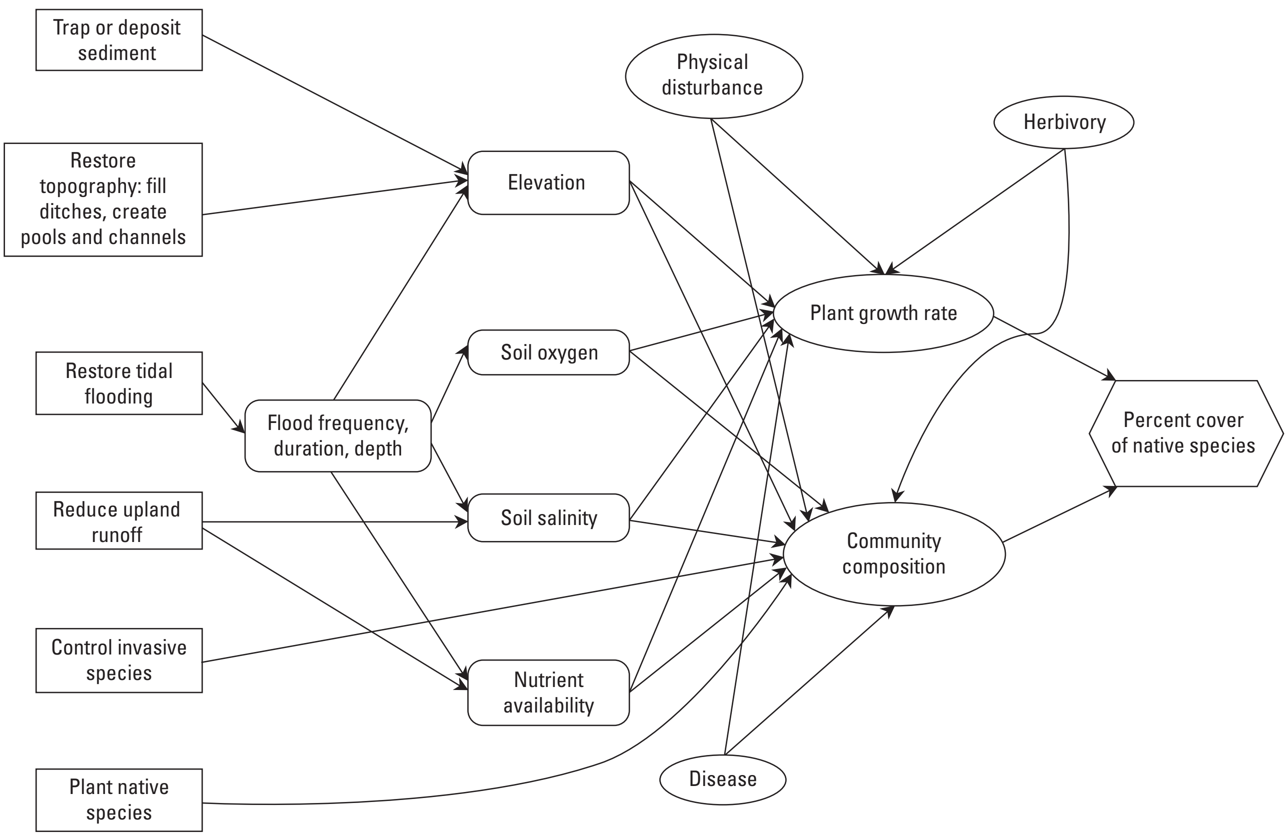



**Figure 1.1.** Influence diagram used to estimate percent cover of native vegetation in response to implementing certain management actions.

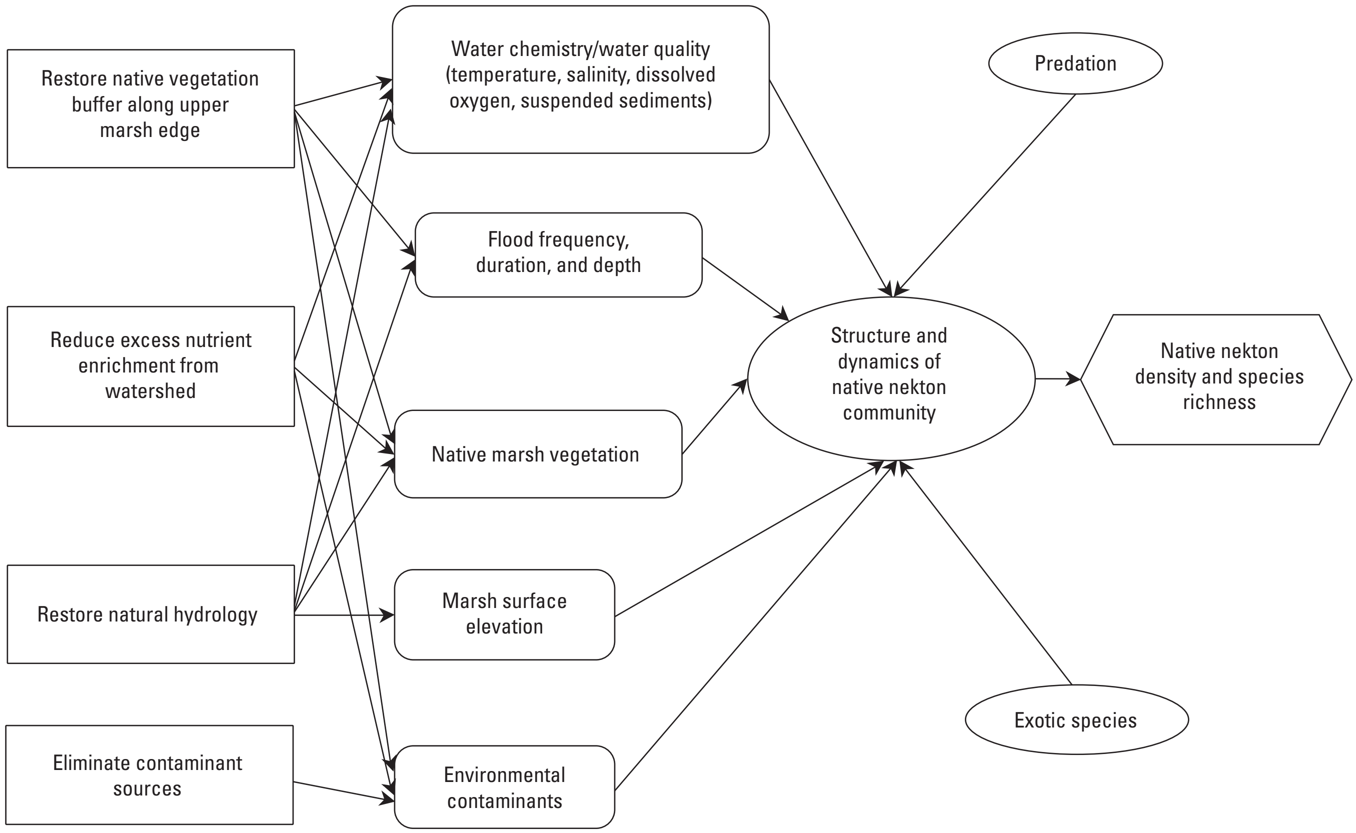



**Figure 1.2.** Influence diagram used to estimate nekton density and species richness in response to implementing certain management actions.

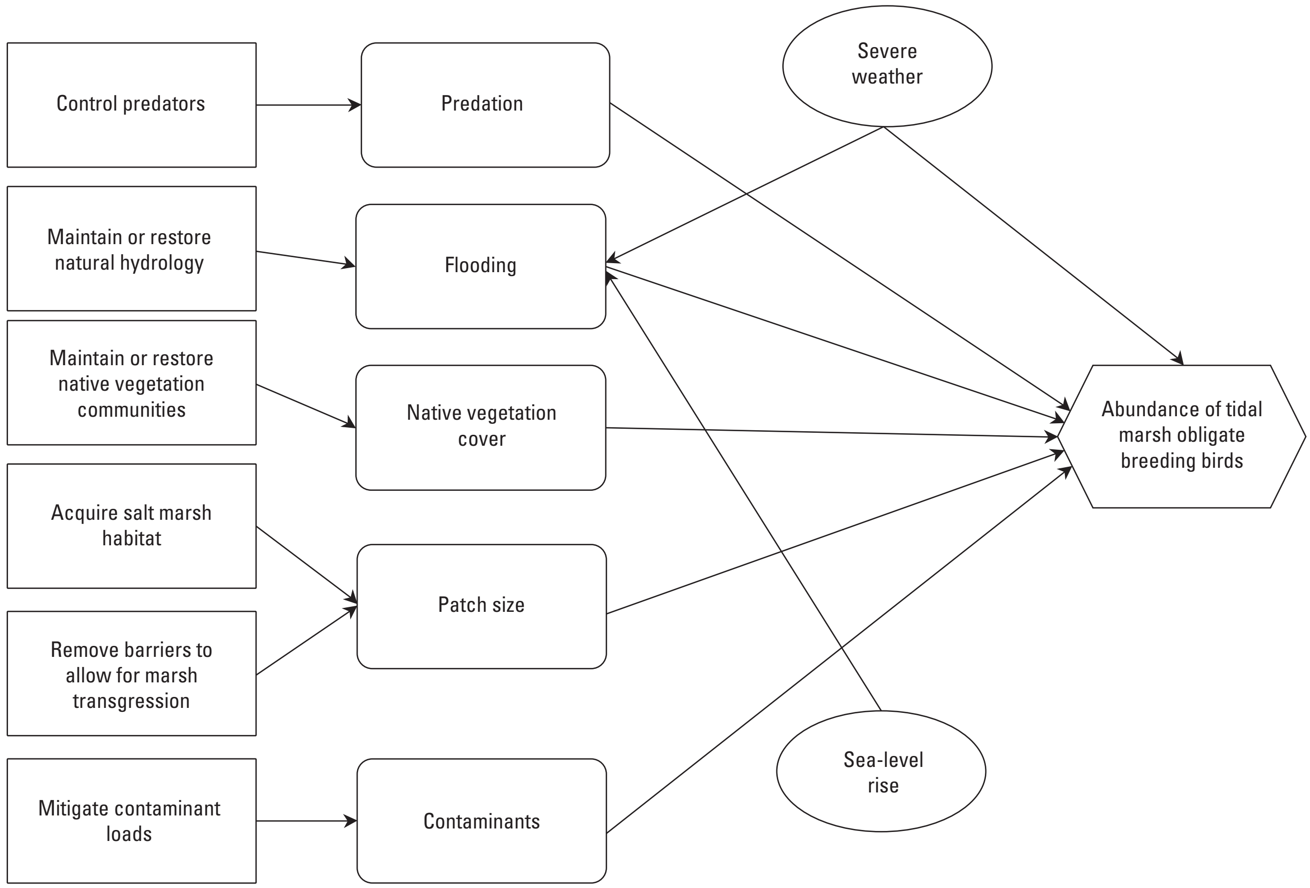



**Figure 1.3.** Influence diagram used to estimate abundance of tidal marsh obligate breeding birds in response to implementing certain management actions.

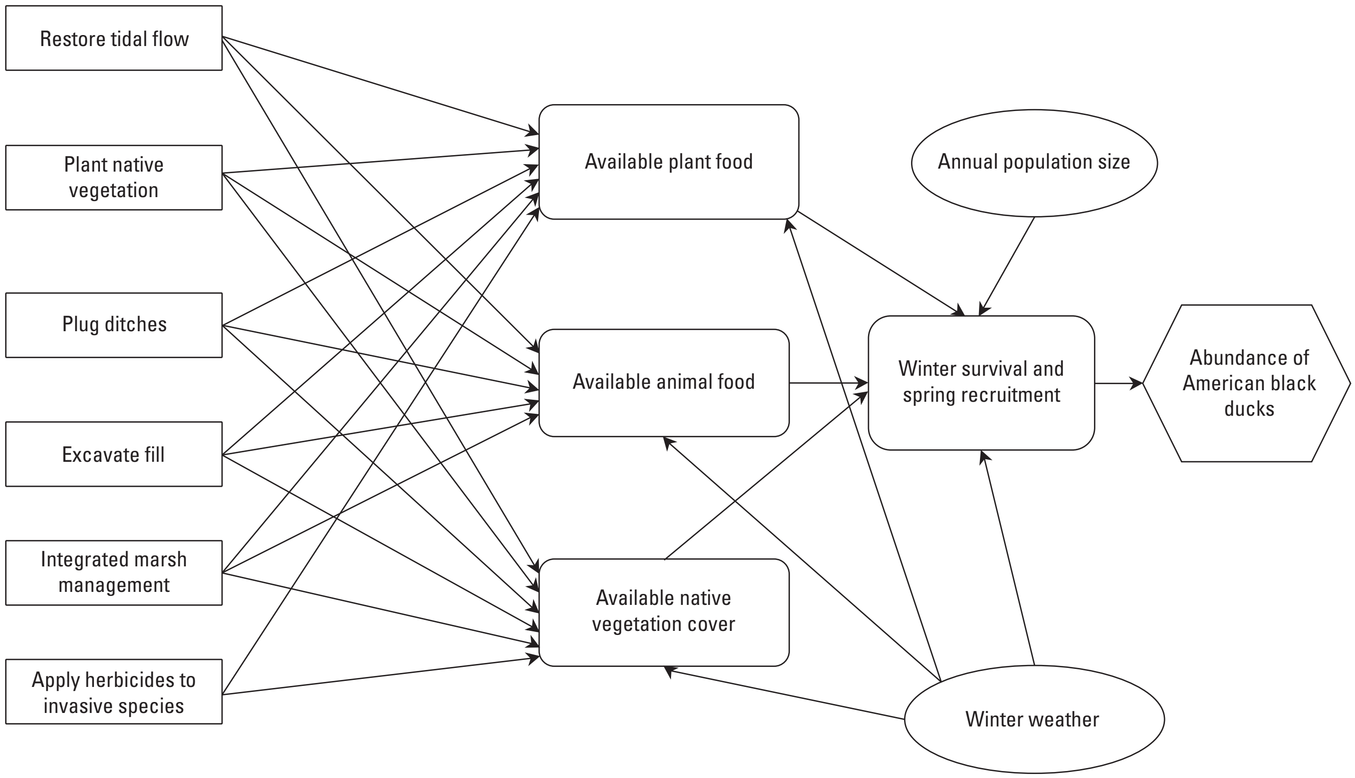



**Figure 1.4.** Influence diagram used to estimate abundance of American black ducks in winter, as indicator species for nonbreeding wetland birds, in response to implementing certain management actions.

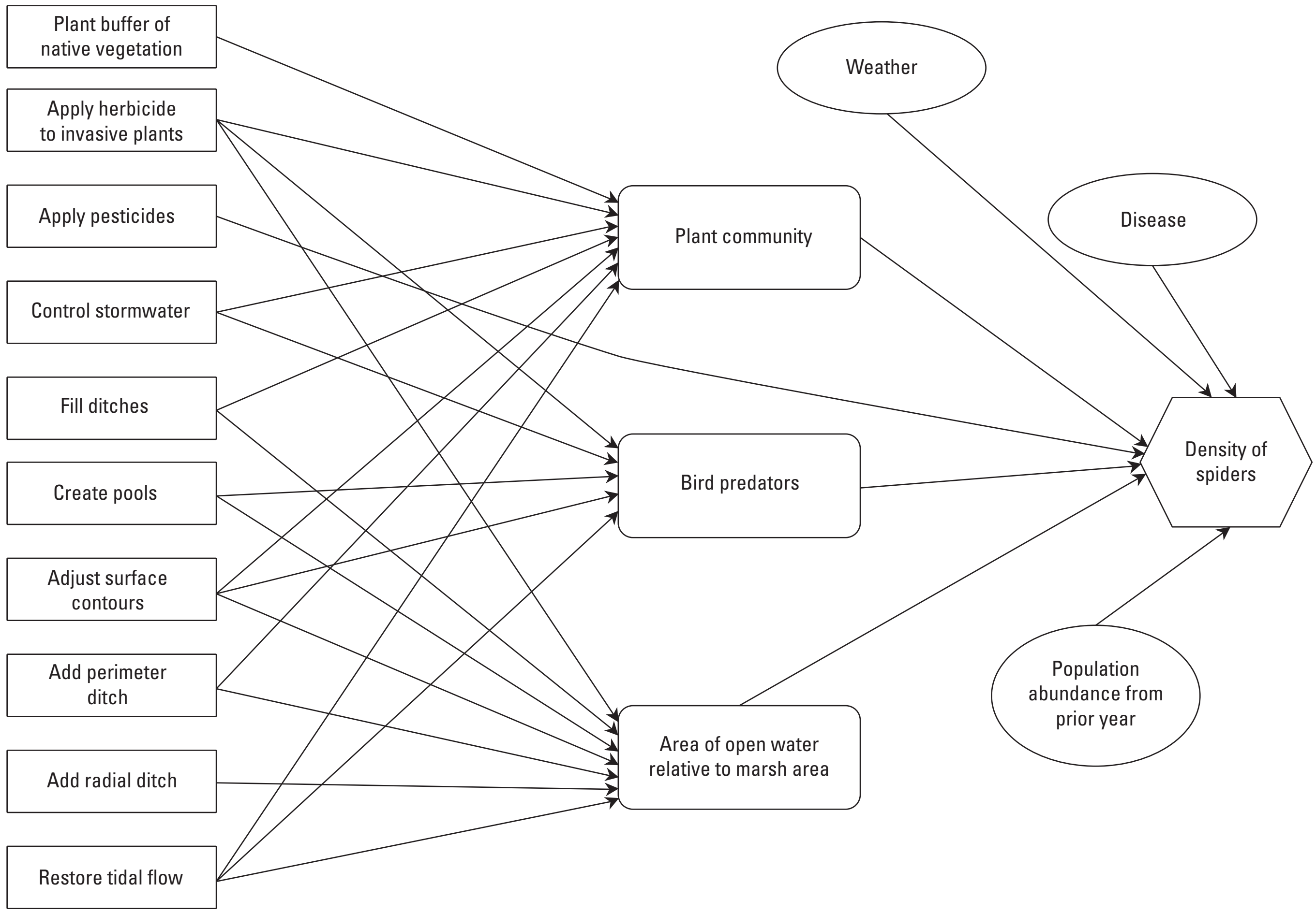



**Figure 1.5.** Influence diagram used to estimate density of spiders, as indicator of trophic health, in response to implementing certain management actions.

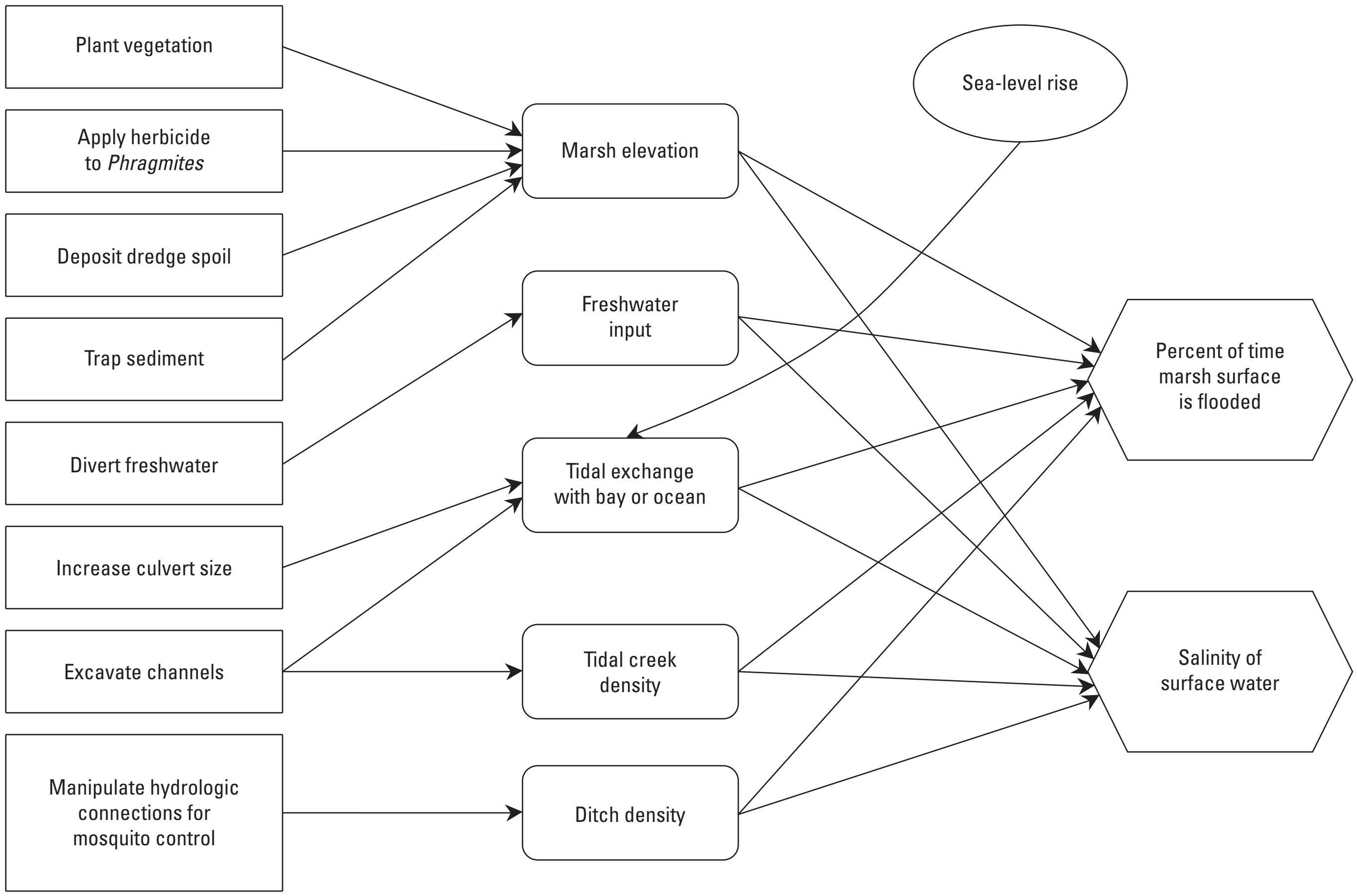



**Figure 1.6.** Influence diagram used to estimate percent of time marsh surface is flooded and salinity of marsh surface water in response to implementing certain management actions.

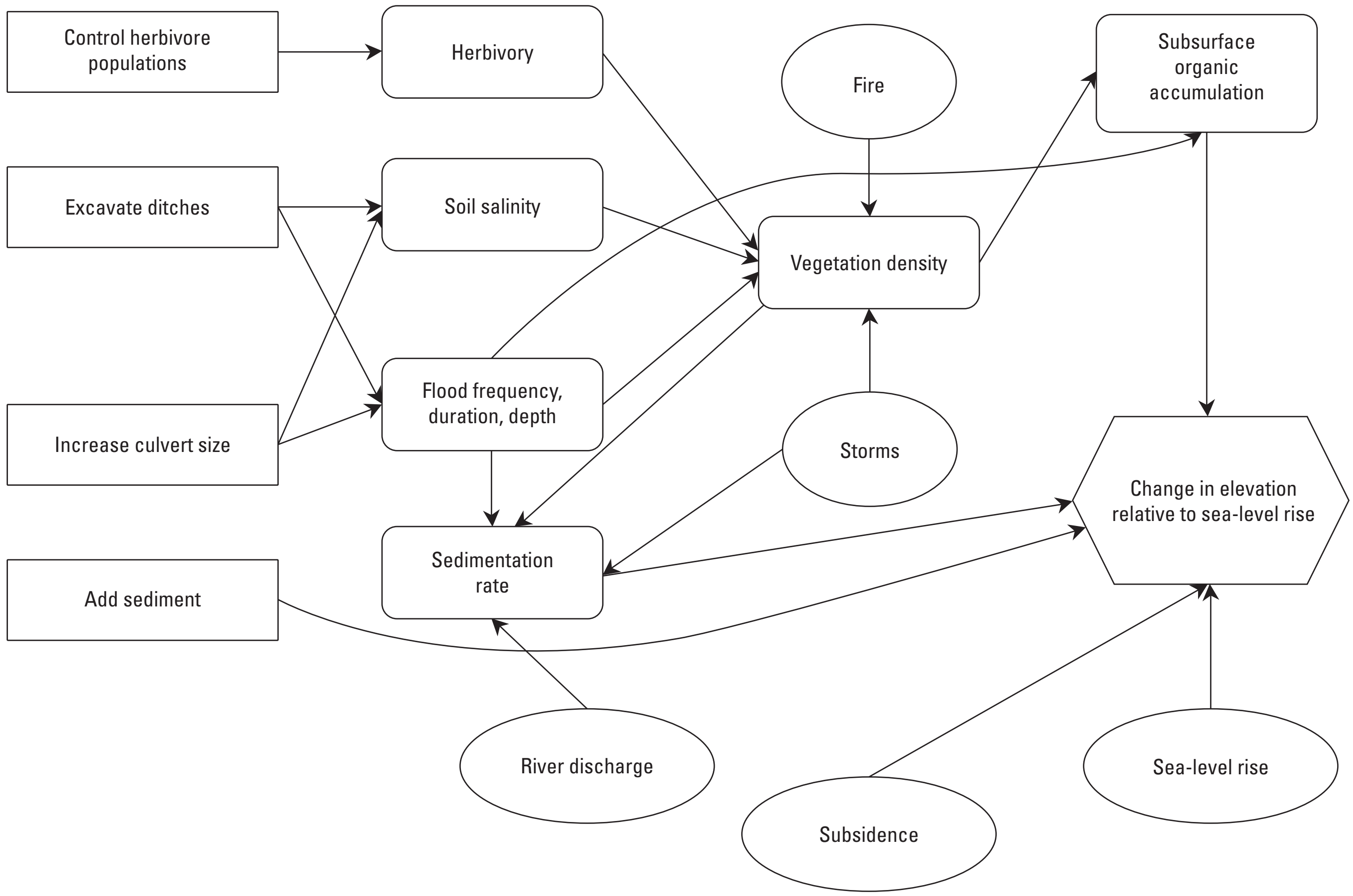



**Figure 1.7.** Influence diagram used to estimate change in elevation of the marsh surface relative to sea-level rise in response to implementing certain management actions.

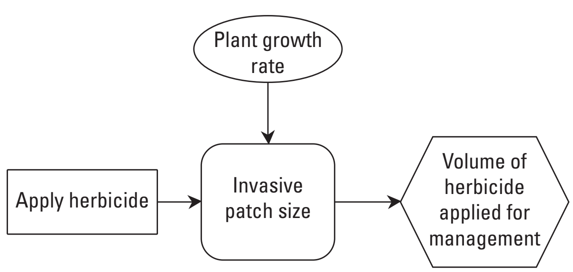


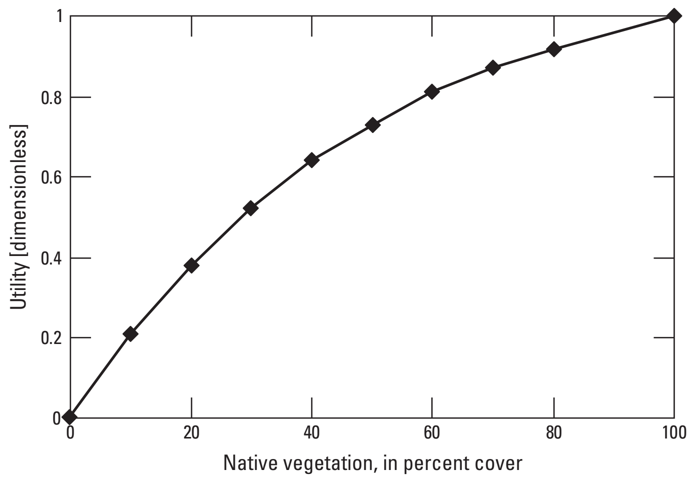

**Figure 1.8.** Influence diagram used to estimate volume of herbicide that would be applied if decision was made to use chemical control for removing unwanted vegetation.

# Appendix 2. Utility Functions for the Rhode Island National Wildlife Refuge Complex

Utilities [$u(x)$] are derived as monotonically increasing, monotonically decreasing, or step functions over the range of performance metric $x$. In the functions in figures 2.1 through 2.10, $x$, *Low*, *High*, and $\rho$ are expressed in performance metric units; *Low* and *High* represent the endpoints of the given metric range for the Rhode Island National Wildlife Refuge Complex; 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.

## Reference Cited

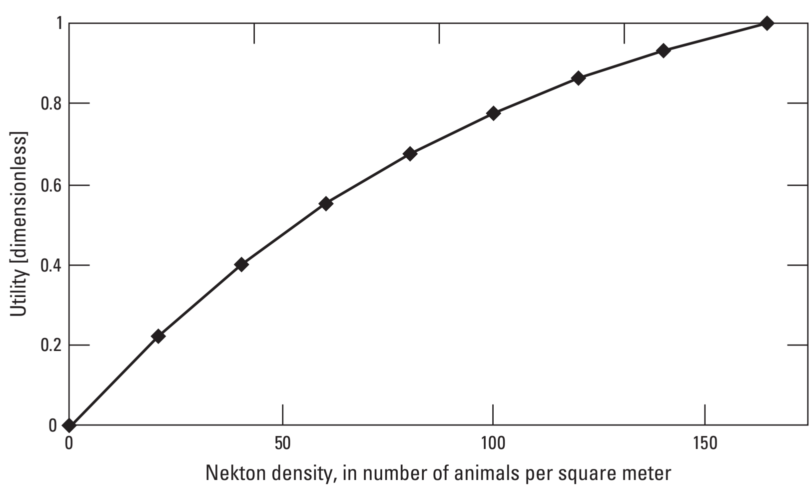
Neckles, H.A., Lyons, J.E., Guntenspergen, G.R., Shriver, W.G., and Adamowicz, S.C., 2015, Use of structured decision making to identify monitoring variables and management priorities for salt marsh ecosystems: Estuaries and Coasts, v. 38, no. 4, p. 1215–1232. [Also available at https://doi.org/10.1007/s12237-014-9822-5.]




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

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

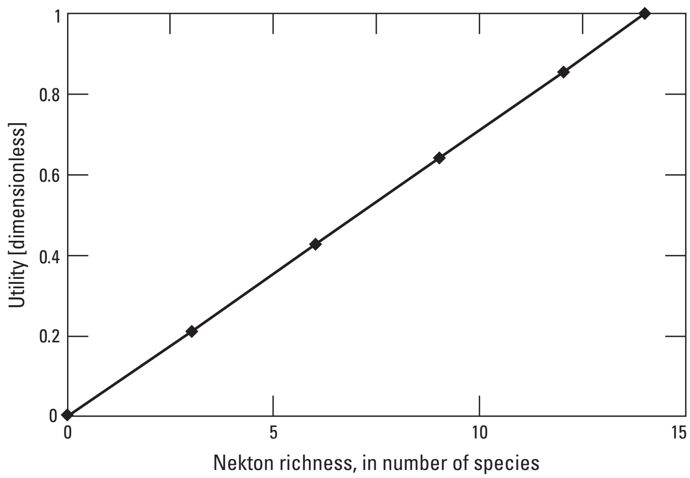
**Figure 2.1.** Native vegetation at the Rhode Island National Wildlife Refuge Complex.




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

where
*Low* = 0
*High* = 165
$\rho$ = 105

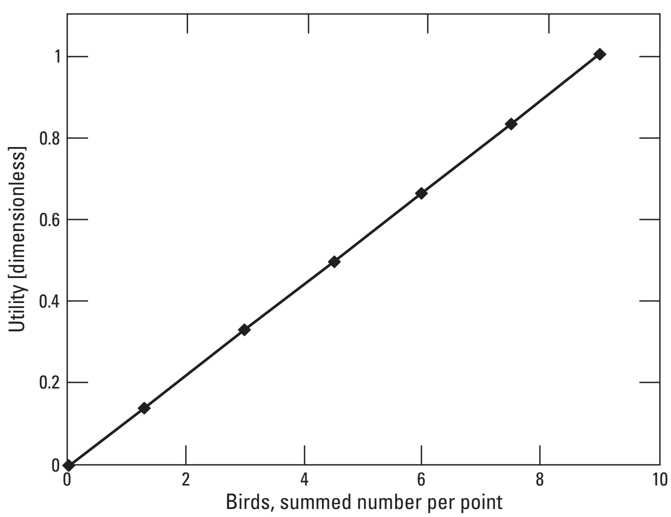
**Figure 2.2.** Native nekton density at the Rhode Island National Wildlife Refuge Complex.




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

where
*Low* = 0
*High* = 14

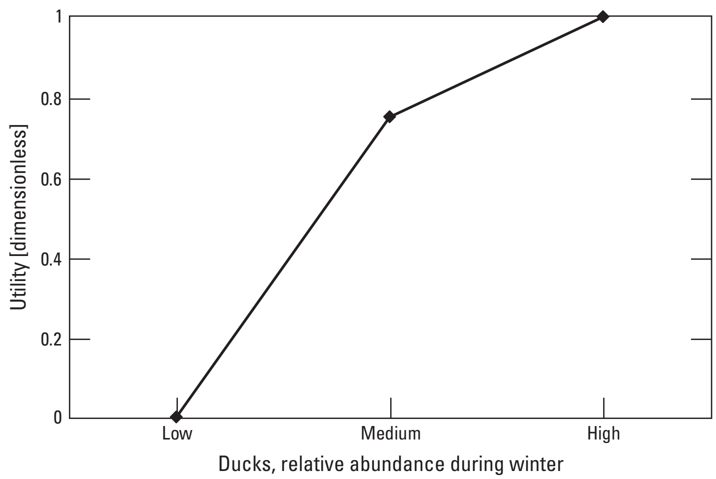
**Figure 2.3.** Native nekton species richness at the Rhode Island National Wildlife Refuge Complex.




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

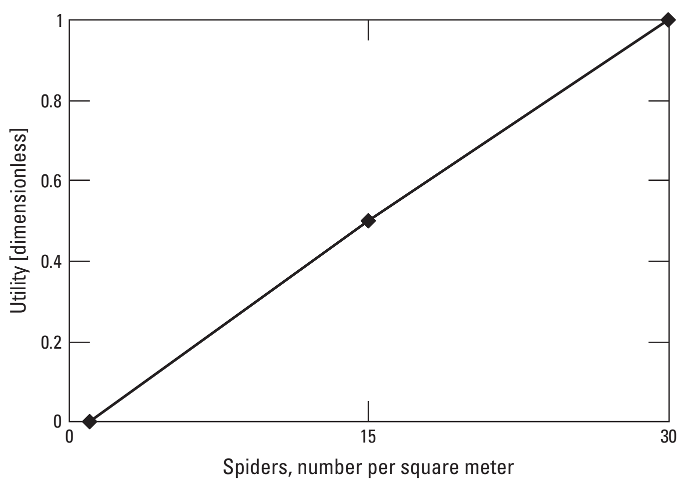
where
*Low* = 0
*High* = 9

**Figure 2.4.** Tidal marsh obligate birds at the Rhode Island National Wildlife Refuge Complex.




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

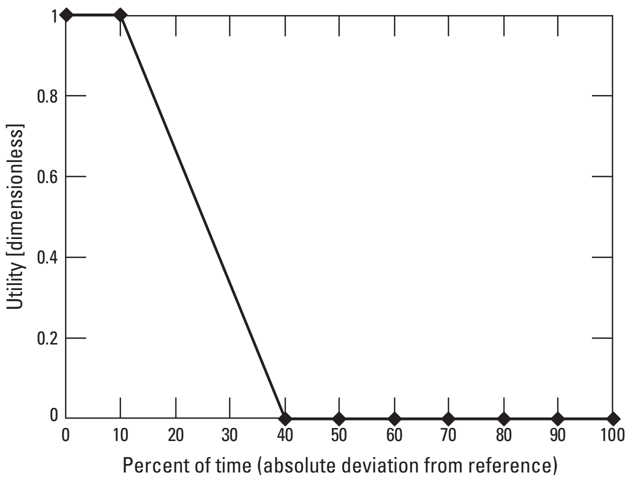
**Figure 2.5.** American black ducks at the Rhode Island National Wildlife Refuge Complex.




If $x \leq 15$, then $u(x) = 0.5 \times \frac{x-1}{14}$

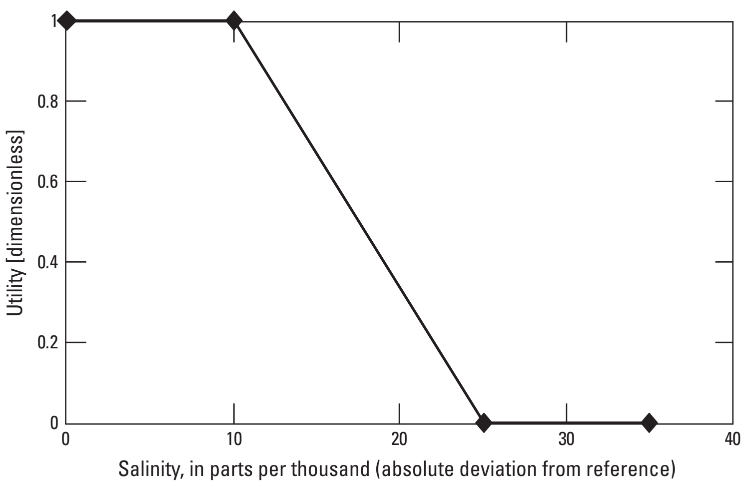
If $x > 15$, then $u(x) = 0.5 + (0.5 \times \frac{x-15}{15})$

**Figure 2.6.** Marsh spiders at the Rhode Island National Wildlife Refuge Complex.



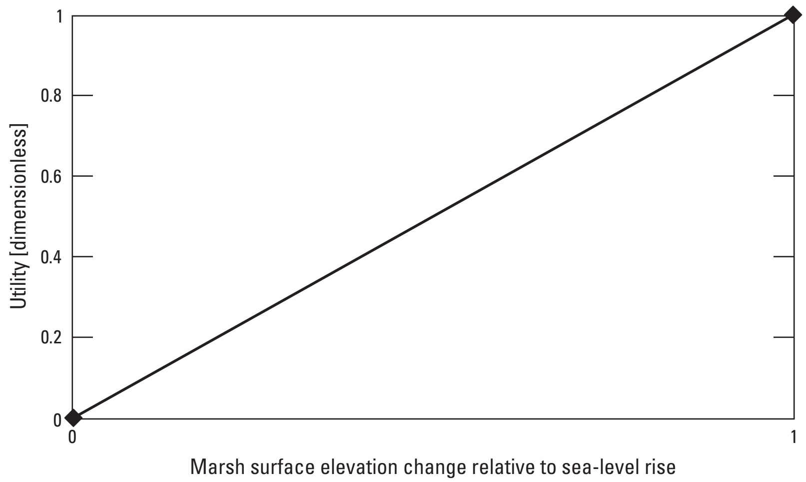

If $x \leq 10$, then $u(x) = 1$
If $x \geq 40$, then $u(x) = 0$
If $10 < x < 40$, then $u(x) = 1 - \frac{x-10}{30}$

**Figure 2.7.** Duration of surface flooding at the Rhode Island National Wildlife Refuge Complex.




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

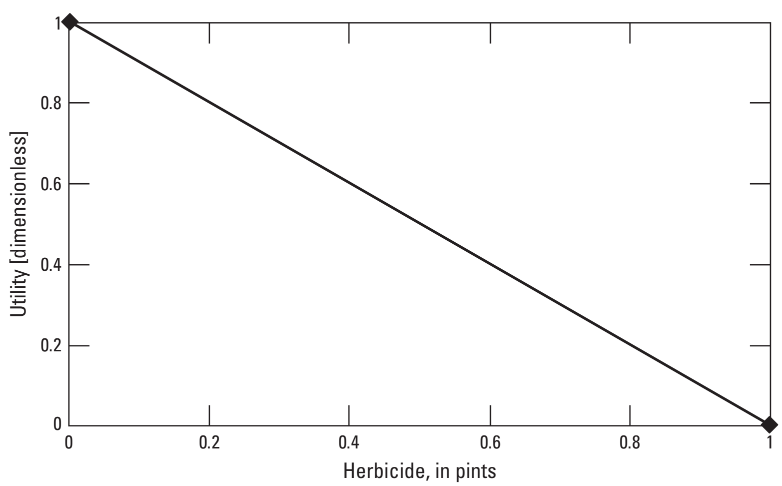
**Figure 2.8.** Salinity of surface water at the Rhode Island National Wildlife Refuge Complex.




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

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

**Figure 2.9.** Change in marsh surface elevation relative to sea-level rise at the Rhode Island National Wildlife Refuge Complex.




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

where
*Low* = 0
*High* = 1

**Figure 2.10.** Application of herbicides at the Rhode Island National Wildlife Refuge Complex.

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Laurel, MD 20708-4039
https://www.usgs.gov/centers/pwrc

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