# Optimization of Salt Marsh Management at the Stewart B. McKinney National Wildlife Refuge, Connecticut, Through Use of Structured Decision Making

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

**Cover.** Photograph of salt marsh habitat at Great Meadows Unit, Stewart B. McKinney National Wildlife Refuge, in Stratford, Connecticut; photograph by Kristina Vagos, 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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DAVID BERNHARDT, Secretary

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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

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 |
| USGS | U.S. Geological Survey |

# Optimization of Salt Marsh Management at the Stewart B. McKinney National Wildlife Refuge, Connecticut, Through Use of Structured Decision Making

By Laurel E. Low,[1] Hilary A. Neckles,[2] James E. Lyons,[2] Jessica L. Nagel,[2] Susan C. Adamowicz,[3] Toni Mikula,[3] Kristina Vagos,[3] and Richard Potvin[3]

## 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 tidal marsh management decisions at the Stewart B. McKinney National Wildlife Refuge in Connecticut. Refuge biologists, refuge managers, and research scientists identified multiple potential management actions to improve the ecological integrity of two marsh management 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 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 $1,190,000, but that further expenditures may yield diminishing return on investment. Management actions in optimal portfolios at total costs less than $1,190,000 included controlling avian predators in both management units, managing stormwater on lands adjacent to one marsh management unit, and removing a tide gate and breaching a dike to improve tidal flow in the other marsh management unit. The management benefits were derived from expected increases in the numbers of spiders (as an indicator of trophic health) and tidal marsh obligate birds, and an expected decrease in the use of herbicides to control invasive vegetation. The prototype presented here provides a framework for decision making at the Stewart B. McKinney National Wildlife Refuge 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 refuges.

## 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,

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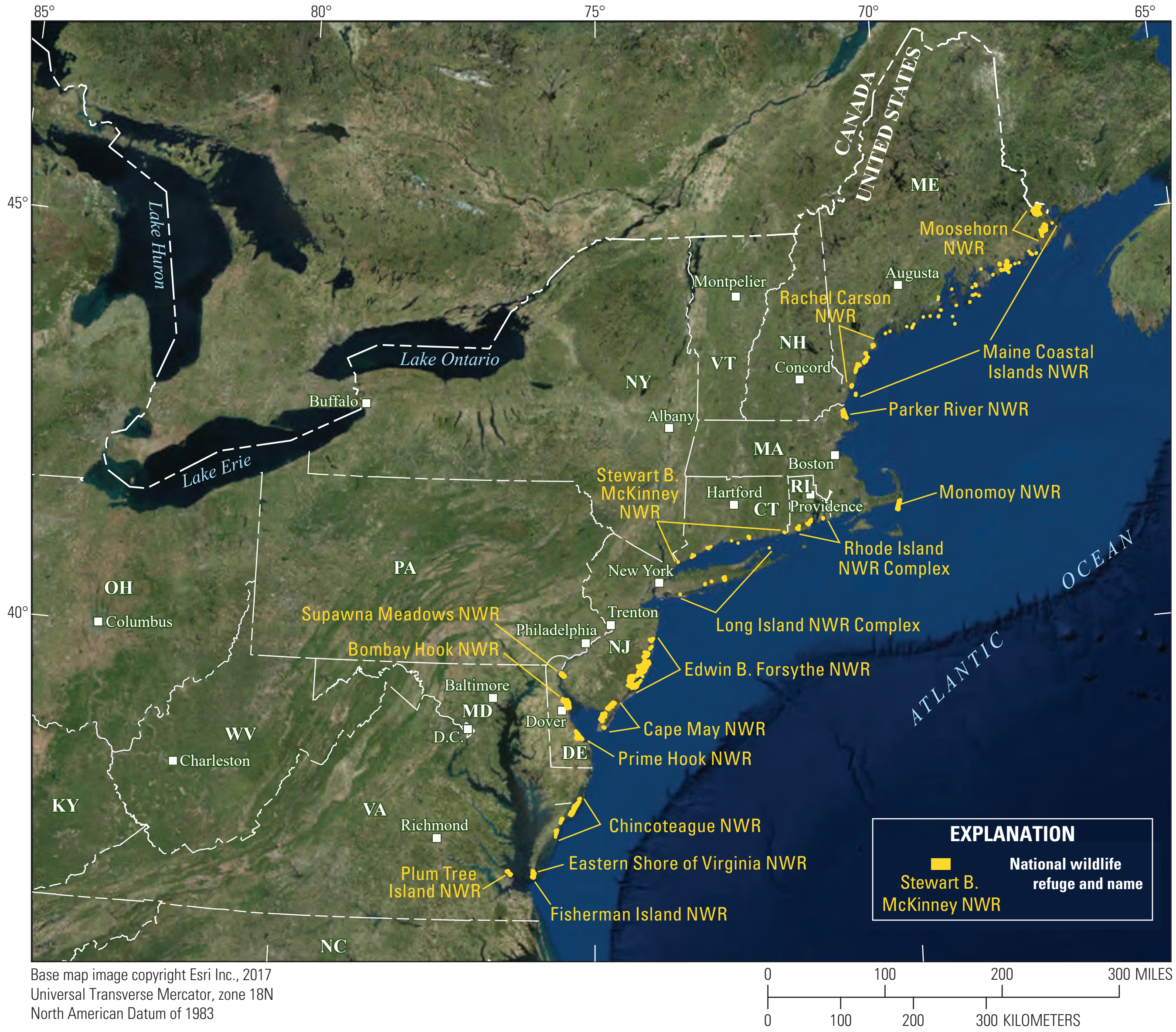
[1] Yale University.

[2] U.S. Geological Survey.

[3] 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 Stewart B. McKinney National Wildlife Refuge protects about 200 hectares (ha) of salt marsh bordering Long Island Sound in Stratford and Westbrook, Connecticut (fig. 2). The refuge’s salt marsh provides critical nesting and



Base map image copyright Esri Inc., 2017
Universal Transverse Mercator, zone 18N
North American Datum of 1983

**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.

Base map image copyright Esri Inc., 2017
Universal Transverse Mercator, Zone 18N
North American Datum of 1983

**Figure 2.** Maps showing salt marsh management units at the Stewart B. McKinney National Wildlife Refuge in Connecticut. *A*, Great Meadows unit in Stratford, Connecticut, and *B*, Salt Meadow unit in Westbrook, Connecticut.

Base map image copyright Esri Inc., 2017
Universal Transverse Mercator, Zone 18N
North American Datum of 1983

**Figure 2.** Maps showing salt marsh management units at the Stewart B. McKinney National Wildlife Refuge in Connecticut. *A*, Great Meadows unit in Stratford, Connecticut, and *B*, Salt Meadow unit in Westbrook, Connecticut.—Continued

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 (Steinkamp, 2008; National Audubon Society, 2020a, b; U.S. North American Bird Conservation Initiative, 2020). The salt marsh also provides important foraging habitat for wading birds (such as  Great and Snowy Egrets) during breeding and migratory seasons (National Audubon Society 2020a, b). The primary threats to this habitat are marsh loss, fragmentation, and degradation associated with increasing human activity within 1,000 meters (m) of the refuge boundary, spread of the invasive reed *Phragmites australis* (hereafter referred to as *Phragmites*), and marsh submergence associated with rising sea level (Potvin, 2017; National Audubon Society 2020a, b; S.C. Adamowicz and T. Mikula, FWS, unpub. data, 2017). Salt-marsh management goals for the refuge focus on maintaining, restoring, and enhancing critical habitat for breeding, migrating, and wintering birds. 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 Stewart B. McKinney 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 two marsh management units at the refuge (fig. 2), 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 Stewart B. McKinney National Wildlife Refuge.

## Description of Study Area

The Stewart B. McKinney National Wildlife Refuge comprises 10 separate parcels along the coast of Connecticut (fig. 1). Two of the refuge's parcels, the Great Meadows and Salt Meadow marsh management units, protect extensive salt marsh habitat along this highly developed shoreline and are the subject of this study. The Great Meadows marsh management unit (fig. 2*A*) in Stratford contains about 173 ha of salt marsh bounded on the northern side by industrial and commercial development and on the southern side by Lewis Gut, an embayment that is connected to Long Island Sound. Dikes interrupt tidal flow to the northern and northeastern reaches of the marsh management unit. Although the northeastern section of the marsh management unit is moderately ditched, the marsh management unit contains the largest segment of unditched high salt marsh in Connecticut (Potvin, 2017). The Salt Meadow marsh management unit (fig. 2*B*) in Westbrook contains about 25 ha of salt marsh along the Menunketesuck River. The majority of land within 150 m of the unit boundary is forest. The marsh management unit is bisected by a railroad bridge over the river that may restrict tidal flow. The salt marsh is heavily ditched throughout the entire Salt Meadow management unit. During summer 2012, average surface-water salinities were about 27 parts per thousand (polyhaline as defined by Cowardin and others, 1979) within both marsh management units (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. 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.

**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; See also Neckles and others (2015)]

| 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 marsh management 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.

# Application to the Stewart B. McKinney National Wildlife Refuge

In January 2018, FWS regional biologists, biologists and managers from seven northeastern NWR administrative units and USGS and Yale University research scientists (table 2) participated in a 1.5-day rapid-prototyping workshop to apply the regional structured decision-making framework to the Maine Coastal Islands, Monomoy, Moosehorn, Parker River, Rachel Carson, and Stewart B. McKinney National Wildlife Refuges. 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 the Great Meadows and Salt Meadow marsh management units at the Stewart B. McKinney National Wildlife Refuge and estimated the total cost of implementation over a 5-year period; the specific years of implementation were not identified in this prototype. Potential actions to enhance salt marsh integrity ranged from targeted efforts that restore hydrologic connections, control predators, or protect shorelines to large-scale projects that alter marsh elevation or vegetation succession (table 3). Participants predicted the outcomes of each management action 5 years after initial 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 judgement for three metrics that lacked assessment data (abundance of American black ducks, density of

**Table 2.** Participants in workshop convened at the Rachel Carson National Wildlife Refuge, Maine, to apply a regional framework for optimizing salt marsh management decisions to six national wildlife refuges in January 2018.

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

| Affiliation | Participant |
|---|---|
| FWS NWR specialists | |
| Maine Coastal Islands NWR | Sara Williams |
| Monomoy NWR | Matthew Hillman |
| Moosehorn NWR | Maurice Mills |
| Moosehorn NWR | Keith Ramos |
| Moosehorn NWR | Ray Brown |
| Parker River NWR | Nancy Pau |
| Parker River NWR | Bill Peterson |
| Rachel Carson NWR | Kathleen O’Brien |
| Rachel Carson NWR | Ryan Kleinert |
| Rachel Carson NWR | Bri Benvenuti |
| Stewart B. McKinney NWR | Richard Potvin |
| Stewart B. McKinney NWR | Kristina Vagos |
| FWS regional experts | |
| Northeast Regional Office | Rachel Katz |
| Northeast Regional Office | Troy Wilson |
| Rachel Carson NWR | Susan Adamowicz |
| Research scientists | |
| USGS Patuxent Wildlife Research Center | James Lyons |
| USGS Patuxent Wildlife Research Center | Hilary Neckles |
| Yale School of Forestry and Environmental Studies | Laurel Low |

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) 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 marsh management unit) that maximizes the total management benefit across all units under varying cost scenarios for 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 increments up to $25,000; in $25,000 increments up to $100,000; in $50,000 increments up to $400,000; in $100,000 increments up to $1 million; and in $500,000 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 Stewart B. McKinney National Wildlife Refuge included adding sediment to the marsh surface to increase elevation; restoring natural hydrology through breaching or removing dikes, removing tide gates, or restoring basin contours or tidal channels; controlling predators; and acquiring land to facilitate marsh migration into adjacent uplands (table 3). For costs ranging from $0 to $4.8 million, the estimated management benefits for individual actions across all metrics, measured as weighted utilities, ranged from 0.410 (for implementing no action in the Great Meadows marsh management unit) to 0.957 (for implementing thin layer deposition followed by vegetation planting in the Salt Meadow marsh management unit coupled with managing stormwater on adjacent lands), out of a maximum possible total management benefit of 1.0 (tables 3 and 4). In each marsh management unit, the alternative with both the lowest management benefit and lowest cost was the “no action” alternative (management 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 either unit) to approximately $6.23 million, the total management benefit at the refuge scale increased from

**Table 3.** Possible management actions for achieving objectives within 2 marsh management units at Stewart B. McKinney National Wildlife Refuge, Connecticut, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.

[Potential management actions, costs, and predicted outcomes developed by workshop participants using expert judgement. Predicted consequences of management actions aided by influence diagrams (app. 1). %, percent; ppt, parts per thousand; TLD, thin layer deposition]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Nekton | | | | | Hydrology | | | |
| | | Native vegetation (% cover) | Density (number of animals per square meter) | Species richness (number) | Tidal marsh obligate birds (summed number per point) | American black ducks use[1] | Spider density (number per square meter) | Duration of surface flooding[2] (%) | Surface-water salinity[2] (ppt) | Marsh surface elevation change relative to sea-level rise[3] | Herbicide application[4] |
| | | | | | Great Meadows | | | | | | |
| A. No action | 0 | 98.4 | 90 | 7 | 1.1 | 2 | 1 | 58.63 | 0 | 0 | 1 |
| B. TLD | 4,500,000 | 98.4 | 94.47 | 7 | 2 | 2 | 30 | 0 | 0 | 1 | 1 |
| C. TLD with planting | 4,781,200 | 99.5 | 95 | 7 | 2 | 2 | 30 | 0 | 0 | 1 | 1 |
| D. Partial TLD | 2,812,500 | 98.4 | 95 | 7 | 2 | 2 | 30 | 0 | 0 | 1 | 1 |
| E. Partial TLD with planting in partial area | 2,988,250 | 98.7 | 95 | 7 | 2 | 2 | 30 | 0 | 0 | 1 | 1 |
| F. Breach dike and recontour basin | 15,000 | 99.5 | 110 | 7 | 1.37 | 2 | 1 | 55 | 0 | 0 | 0 |
| G. Remove tide gate | 5,000 | 99.5 | 110 | 7 | 1.37 | 2 | 1 | 55 | 0 | 0 | 1 |
| H. Remove dike and recontour basin | 15,000 | 99.5 | 110 | 7 | 1.6 | 2 | 1 | 55 | 0 | 0 | 1 |
| I. Move dikes | 1,500 | 98.4 | 94.47 | 7 | 1.37 | 2 | 1 | 55 | 0 | 0 | 1 |
| J. Channels: stabilize banks | 25,000 | 98.4 | 94.47 | 7 | 1.37 | 2 | 1 | 55 | 0 | 0 | 1 |
| K. Channels: create new | 390,000 | 99.5 | 110 | 7 | 1.6 | 2 | 1 | 55 | 0 | 0 | 1 |
| L. Culverts: additional under road | 240,000 | 98.4 | 110 | 7 | 1.6 | 2 | 1 | 55 | 2 | 0 | 1 |
| M. Marsh management for mosquitoes | 65,000 | 99.5 | 110 | 7 | 1.6 | 2 | 1 | 55 | 0 | 0 | 0 |
| N. Stormwater management on adjacent lands | 525,000 | 99 | 110 | 7 | 1.1 | 2 | 1 | 55 | 0 | 0 | 1 |
| O. Predator control | 10,000 | 98.4 | 90 | 7 | 1.6 | 2 | 1 | 55 | 0 | 0 | 1 |
| P. Lessen wave action and sediment loss | 1,000,000 | 98.4 | 94.47 | 7 | 1.37 | 2 | 1 | 55 | 0 | 0 | 1 |
| Q. C+H+I | 4,797,700 | 99.9 | 120 | 7 | 3 | 2 | 30 | 55 | 0 | 1 | 0 |

**Table 3.** Possible management actions for achieving objectives within 2 marsh management units at Stewart B. McKinney National Wildlife Refuge, Connecticut, estimated costs over 5 years, and predicted outcomes expressed relative to performance metrics.—Continued

[Potential management actions, costs, and predicted outcomes developed by workshop participants using expert judgement. Predicted consequences of management actions aided by influence diagrams (app. 1). %, percent; ppt, parts per thousand; TLD, thin layer deposition]

| Management action | Estimated cost over 5 years (dollars) | Performance metrics | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Native vegetation (% 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] (%) | Surface-water salinity[2] (ppt) | | |
| Salt Meadow | | | | | | | | | | | |
| A. No action | 0 | 98 | 45.11 | 9 | 2.94 | 2 | 1 | 60.85 | 0 | 0 | 0 |
| B. TLD | 1,125,000 | 98 | 45.11 | 9 | 3.5 | 2 | 30 | 0 | 0 | 1 | 0 |
| C. TLD with planting | 1,195,300 | 99 | 45.11 | 9 | 3.5 | 2 | 30 | 0 | 0 | 1 | 0 |
| D. Stormwater management on adjacent lands | 240,000 | 98 | 45.11 | 9 | 3.2 | 2 | 15 | 30 | 1 | 0 | 0 |
| E. Predator control | 10,000 | 98 | 45.11 | 9 | 3 | 2 | 1 | 60.85 | 0 | 0 | 0 |
| F. Facilitate marsh migration | 31,800 | 99 | 45.11 | 9 | 2.94 | 2 | 1 | 60.85 | 0 | 0 | 0 |
| G. C+D | 1,435,300 | 99 | 45.11 | 9 | 3.6 | 2 | 30 | 0 | 1 | 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, lower than sea-level rise; 1, above 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 2 marsh management units at the Stewart B. McKinney National Wildlife Refuge, Connecticut.

[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]

| 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 | | | |
| Great Meadows | | | | | | | | | | | |
| A. No action | 0.119 | 0.040 | 0.035 | 0.031 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.410 |
| B. TLD | 0.119 | 0.041 | 0.035 | 0.056 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.000 | 0.856 |
| C. TLD with planting | 0.120 | 0.041 | 0.035 | 0.056 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.000 | 0.857 |
| D. Partial TLD | 0.119 | 0.041 | 0.035 | 0.056 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.000 | 0.856 |
| E. Partial TLD with planting in partial area | 0.120 | 0.041 | 0.035 | 0.056 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.000 | 0.856 |
| F. Breach dike and recontour basin | 0.120 | 0.044 | 0.035 | 0.038 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.060 | 0.482 |
| G. Remove tide gate | 0.120 | 0.044 | 0.035 | 0.038 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.422 |
| H. Remove dike and recontour basin | 0.120 | 0.044 | 0.035 | 0.044 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.428 |
| I. Move dikes | 0.119 | 0.041 | 0.035 | 0.038 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.419 |
| J. Channels: stabilize banks | 0.119 | 0.041 | 0.035 | 0.038 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.419 |
| K. Channels: create new | 0.120 | 0.044 | 0.035 | 0.044 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.428 |
| L. Culverts: additional under road | 0.119 | 0.044 | 0.035 | 0.044 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.428 |
| M. Marsh management for mosquitoes | 0.120 | 0.044 | 0.035 | 0.044 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.060 | 0.488 |
| N. Stormwater management on adjacent lands | 0.120 | 0.044 | 0.035 | 0.031 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.414 |
| O. Predator control | 0.119 | 0.040 | 0.035 | 0.044 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.424 |
| P. Lessen wave action and sediment loss | 0.119 | 0.041 | 0.035 | 0.038 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.000 | 0.419 |
| Q. C+H+I | 0.120 | 0.045 | 0.035 | 0.083 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.060 | 0.948 |

**Table 4.** Normalized predicted outcomes and estimated total management benefits of possible management actions within 2 marsh management units at the Stewart B. McKinney National Wildlife Refuge, Connecticut.—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]

| 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 | | | |
| Salt Meadow | | | | | | | | | | | |
| A. No action | 0.119 | 0.028 | 0.045 | 0.082 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.060 | 0.518 |
| B. TLD | 0.119 | 0.028 | 0.045 | 0.097 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.060 | 0.954 |
| C. TLD with planting | 0.120 | 0.028 | 0.045 | 0.097 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.060 | 0.954 |
| D. Stormwater management on adjacent lands | 0.119 | 0.028 | 0.045 | 0.089 | 0.075 | 0.045 | 0.037 | 0.110 | 0.000 | 0.060 | 0.607 |
| E. Predator control | 0.119 | 0.028 | 0.045 | 0.083 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.060 | 0.520 |
| F. Facilitate marsh migration | 0.120 | 0.028 | 0.045 | 0.082 | 0.075 | 0.000 | 0.000 | 0.110 | 0.000 | 0.060 | 0.519 |
| G. C+D | 0.120 | 0.028 | 0.045 | 0.100 | 0.075 | 0.090 | 0.110 | 0.110 | 0.220 | 0.060 | 0.957 |

0.928 to 1.905 (a 105 percent increase; table 5) out of a possible maximum of 2.0 (the maximum possible management benefit of 1.0 for any management action, summed across the two marsh management units). Graphical analysis showed a fairly consistent increase in management benefit as costs increased to $1.19 million (fig. 3, portfolio 9). Portfolio 9 represented the turning point in the cost-benefit plot. As expenditures increased beyond the cost of portfolio 9, total management benefit continued to increase but at a lower rate, yielding diminishing returns on investment; there was very little gain in management benefit for expenditures greater than about $3.9 million (fig. 3, portfolio 14).

Several patterns emerged relative to management actions selected within the set of portfolios that yielded the greatest total management benefit per unit cost (table 5, portfolios 2 through 9). The lowest-cost portfolios (total cost up to $250,000) always included predator control at one or the other of the marsh management units. In addition, portfolios at the Great Meadows marsh management unit included actions to restore hydrologic connections or integrated management for mosquito control, whereas portfolios at the Salt Meadow marsh management unit included primarily stormwater management on adjacent lands. In contrast, some management actions were never or rarely included in the portfolios yielding the greatest benefit per cost. For example, stormwater management on adjacent lands and adding culverts or channels were never selected for the Great Meadows marsh management unit, and facilitating marsh migration into the uplands was never selected for the Salt Meadow marsh management unit. At both marsh management units, thin layer deposition was only selected when the available budget exceeded $1 million.

Examination of the refuge-scale metric responses to actions included in portfolio 9, which is the turning point in the cost-benefit plot (fig. 3), revealed how implementation could affect specific management objectives. The actions included were predicted to achieve large gains in the overall management benefits derived from density of spiders (as an indicator of trophic health), duration of flooding, and the capacity of marsh elevation to keep pace with sea-level rise and modest gains in the benefits derived from numbers of tidal marsh obligate birds and herbicide application (fig. 4). Ecologically, the combination of actions in portfolio 9 may result in an average 32 percent increase in tidal marsh obligate bird counts (averaged across both marsh management units),

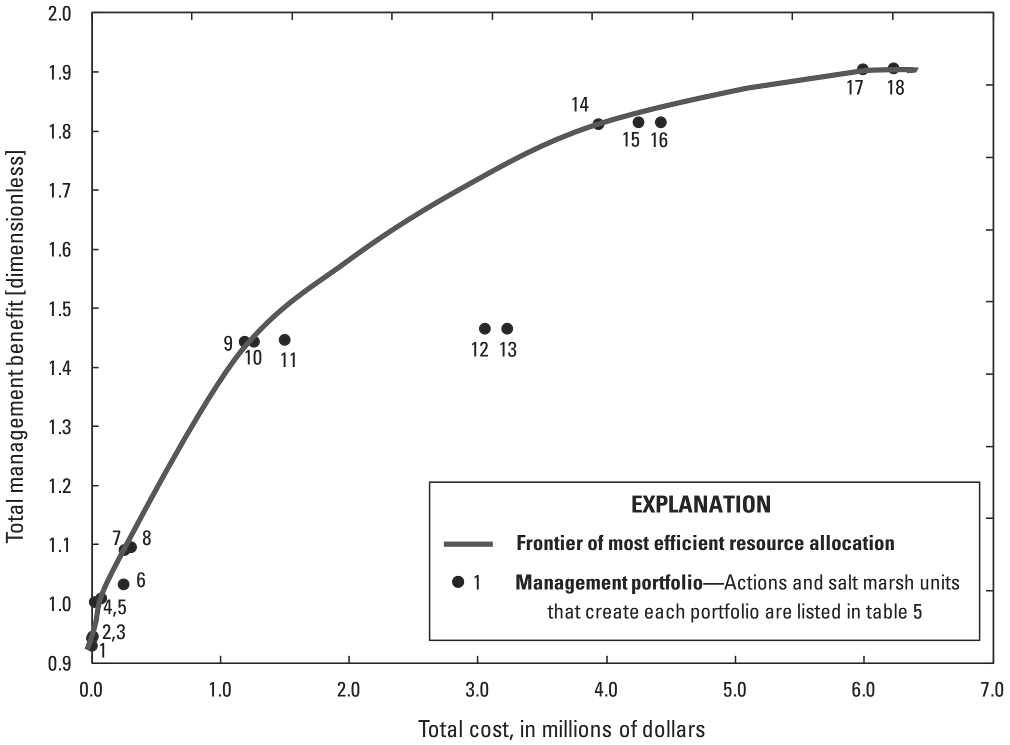


**Figure 3.** Predicted total management benefit of various portfolios, expressed as weighted utilities, relative to total cost at the Stewart B. McKinney National Wildlife Refuge in Connecticut. Each portfolio (dot with number) represents a combination of two management actions, one per marsh management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

**Table 5.** Actions included in various management portfolios to maximize the total management benefits subject to increasing cost constraints at the Stewart B. McKinney National Wildlife Refuge, Connecticut.

[Letter designations for actions refer to specific actions and are listed in tables 3 and 4. Portfolios represent the combination of actions, one per 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 total cost represents the sum of costs estimated for each action included in the portfolio. The maximum possible total management benefit for the refuge is 2, derived as the maximum possible total management benefit of 1.0 for any management action within one management unit, summed across 2 units]

| Portfolio | Marsh management unit | | Total cost (dollars) | Total management benefit |
|---|---|---|---|---|
| | Great Meadows | Salt Meadow | | |
| 1 | A | A | 0 | 0.928 |
| 2 | G | A | 5,000 | 0.940 |
| 3 | O | A | 10,000 | 0.943 |
| 4 | F | E | 25,000 | 1.002 |
| 5 | M | E | 75,000 | 1.008 |
| 6 | O | D | 250,000 | 1.032 |
| 7 | F | D | 255,000 | 1.089 |
| 8 | M | D | 305,000 | 1.095 |
| 9 | M | B | 1,190,000 | 1.442 |
| 10 | M | C | 1,260,300 | 1.442 |
| 11 | M | G | 1,500,300 | 1.445 |
| 12 | D | D | 3,052,500 | 1.464 |
| 13 | E | D | 3,228,250 | 1.464 |
| 14 | D | B | 3,937,500 | 1.810 |
| 15 | D | G | 4,247,800 | 1.813 |
| 16 | E | G | 4,423,550 | 1.813 |
| 17 | Q | C | 5,993,000 | 1.903 |
| 18 | Q | G | 6,233,000 | 1.905 |

53 percent decrease in the deviation of surface flooding from the ideal reference condition, and 1,450 percent increase in spider density (derived as the average difference between the predicted metric scores for the actions implemented in portfolio 9 and the “no-action” alternative; table 3). Implementation of actions in this portfolio was also predicted to improve the capacity for marsh elevation to keep pace with sea-level rise in the Salt Meadow marsh management unit and reduce application of herbicides in the Great Meadows marsh management unit. The management benefits predicted for portfolios 1 through 8, at total costs up to $305,000, were derived primarily from expected improvements in surface-water drainage, presumed increases in densities of spiders and numbers of tidal marsh obligate birds, and reduced need for herbicide application (tables 3 and 4).

# 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 Stewart B. McKinney 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. 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 Stewart B. McKinney National Wildlife Refuge 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 and management strategies to enhance their sustainability (Kirwan and Megonigal, 2013; Roman, 2017). Many salt marshes throughout the northeastern United States are degraded by roads, dikes, railroads, or other obstructions to tidal flow, and salt marsh restoration frequently focuses on reestablishing tidal flow (Konisky and others, 2006; Roman and Burdick, 2012). Actions to restore tidal exchange throughout the Great Meadows marsh management unit were predicted to improve overall management benefit for a relatively low cost. In contrast, thin-layer deposition of sediments to raise marsh elevation is increasingly proposed to enhance sustainability of salt marshes in the northeastern United States (Wigand and others, 2017) and was identified as a potential action to improve the integrity of both marsh management units at the Stewart B. McKinney National Wildlife Refuge with expected high total management benefit (table 4). However, the high cost of implementation restricted this option to the most costly portfolios (table 5, portfolios 9 through 18).

Multiple, interacting factors influence the long-term success of restoration actions in prolonging marsh integrity and improving marsh resilience (Roman, 2017). Future iterations of this decision model can incorporate improved understanding of both implementation costs and marsh responses to management actions. 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). In 2012, surface elevation tables (Lynch and others, 2015) were installed in each marsh management unit to obtain high-resolution measurements

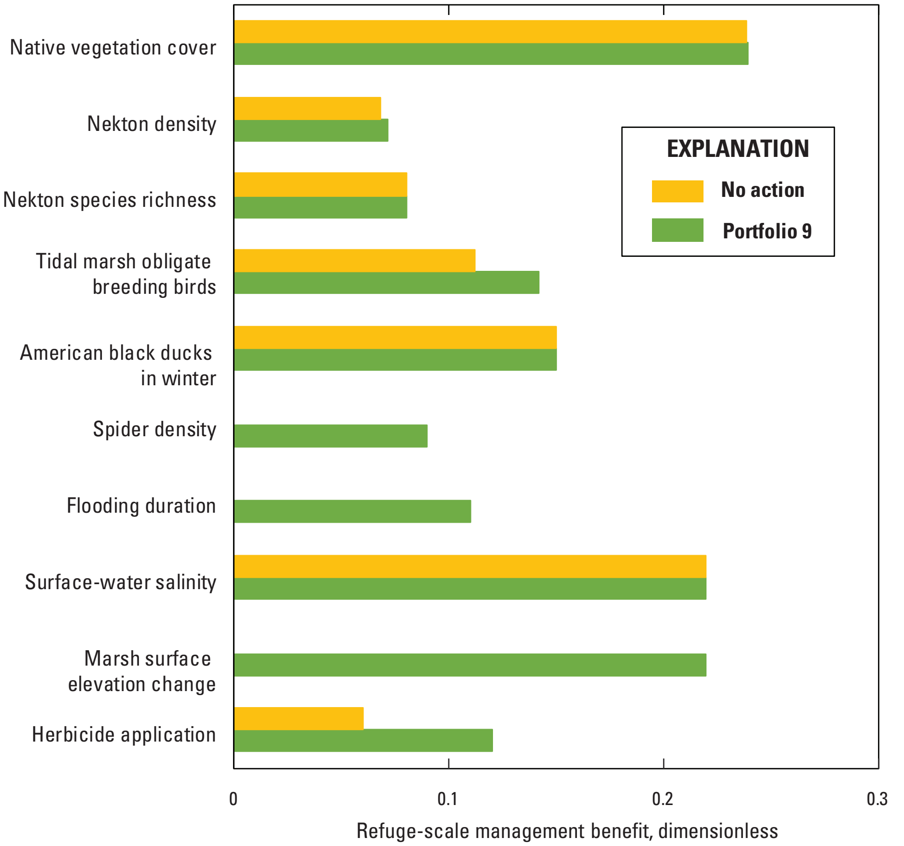


**Figure 4.** Predicted management benefit at the refuge scale for individual performance metrics, expressed as weighted utilities, resulting from implementation of the management actions included in portfolio 9, in comparison to the management benefit from the baseline “no-action” portfolio, at the Stewart B. McKinney National Wildlife Refuge in Connecticut. Baseline (“no-action”) predicted management benefit for spider density, flooding duration, and marsh surface elevation change are zero. The actions included in each portfolio are listed in table 5.

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 areas in which to improve the utility of the prototype for refuge decision making. First, although increasing the rate of marsh elevation gain relative to sea-level rise is a primary management concern at the Stewart B. McKinney National Wildlife Refuge, enhancing elevation directly through sediment deposition may be cost prohibitive for these salt marshes. Therefore, alternative options to reduce the depth and duration of surface flooding, such as digging runnels to improve surface drainage, may be more feasible (Wigand and others, 2017). Additionally, testing targeted actions to mitigate effects of flooding on at-risk species, such as creation of floating islands as nesting sites for saltmarsh sparrows, may be useful (Benvenuti, 2016).

Second, actions to minimize marsh loss through stabilizing channel banks or lessening wave action were excluded from the optimal portfolios. 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 of marsh substrate may help focus decision making on erosion of marsh edges.

Third, although implementing integrated marsh management for mosquito control, which is a comprehensive approach to restoring tidal hydrology and reducing mosquitoes (Rochlin and others, 2012), was predicted to enhance abundance of nekton and tidal marsh obligate birds and reduce application of herbicide for *Phragmites* control at the Great Meadows unit (table 3), the regional environmental health objectives included in this prototype did not accommodate a potential additional benefit of reducing or eliminating use of insecticides to control mosquitoes. The mosquito management plan for the Great Meadows unit emphasized that to minimize use of insecticides on the refuge, hydrologic restoration should be employed where possible to decrease mosquito production (Potvin, 2017). In the future, including an objective in the decision model related to minimizing insecticides would incorporate the effect of integrated marsh management on total pesticide use, including herbicides and insecticides, into the total management benefits.

Finally, the constrained optimizations analyzed in this report were based on approximations of management costs. As salt marsh management is undertaken around the region, a detailed list of actual expenses can be compiled, including staff time for project planning as well as materials, equipment, contracts, and staff time for implementation. This will allow future iterations of the decision model to include more accurate cost estimates.

The prototype model for the Stewart B. McKinney National Wildlife Refuge 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 to determine the background rate of change in the absence of management actions; 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 Stewart B. McKinney National Wildlife Refuge 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 marsh management units are included in optimal management portfolios, to further tailor the model to refuge-specific needs.

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# 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.

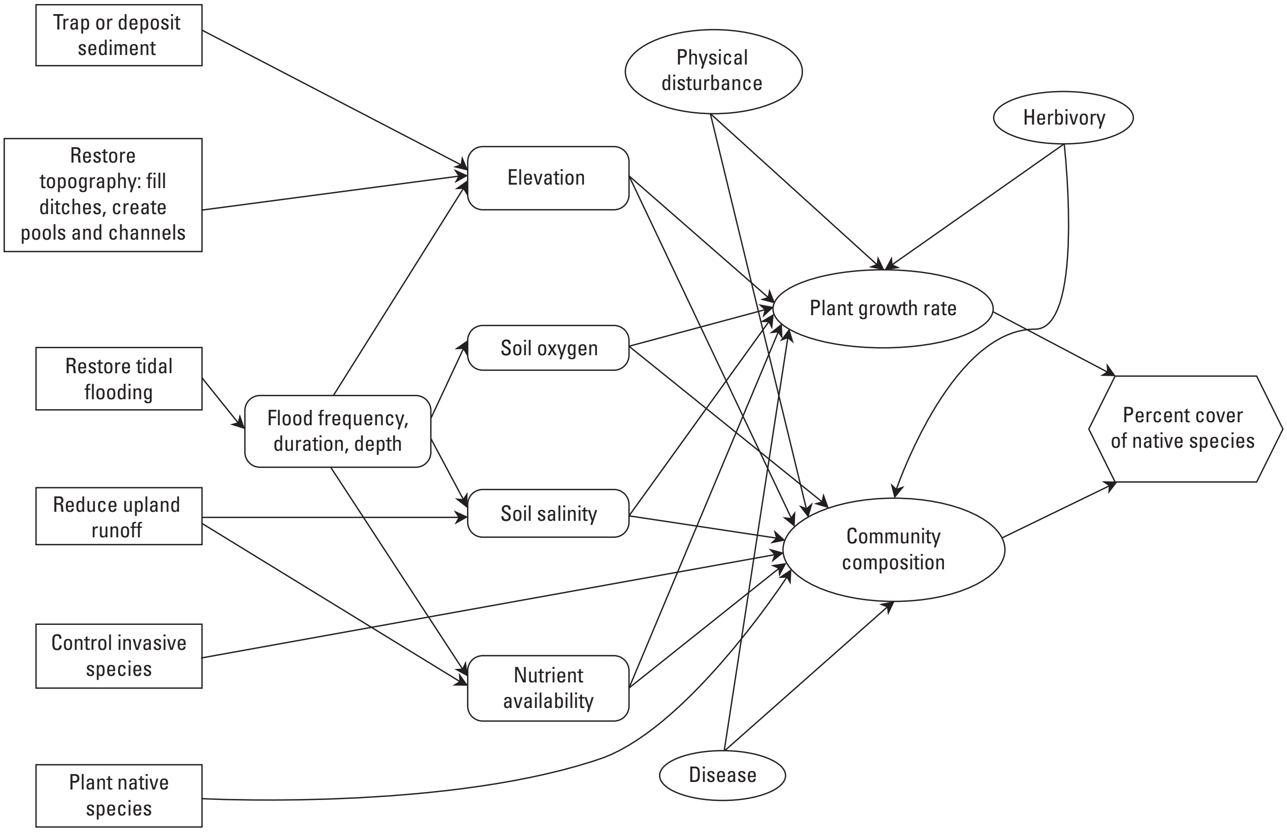

**Figure 1.1.** Influence diagram used to estimate percent cover of native vegetation in response to implementing certain management actions.

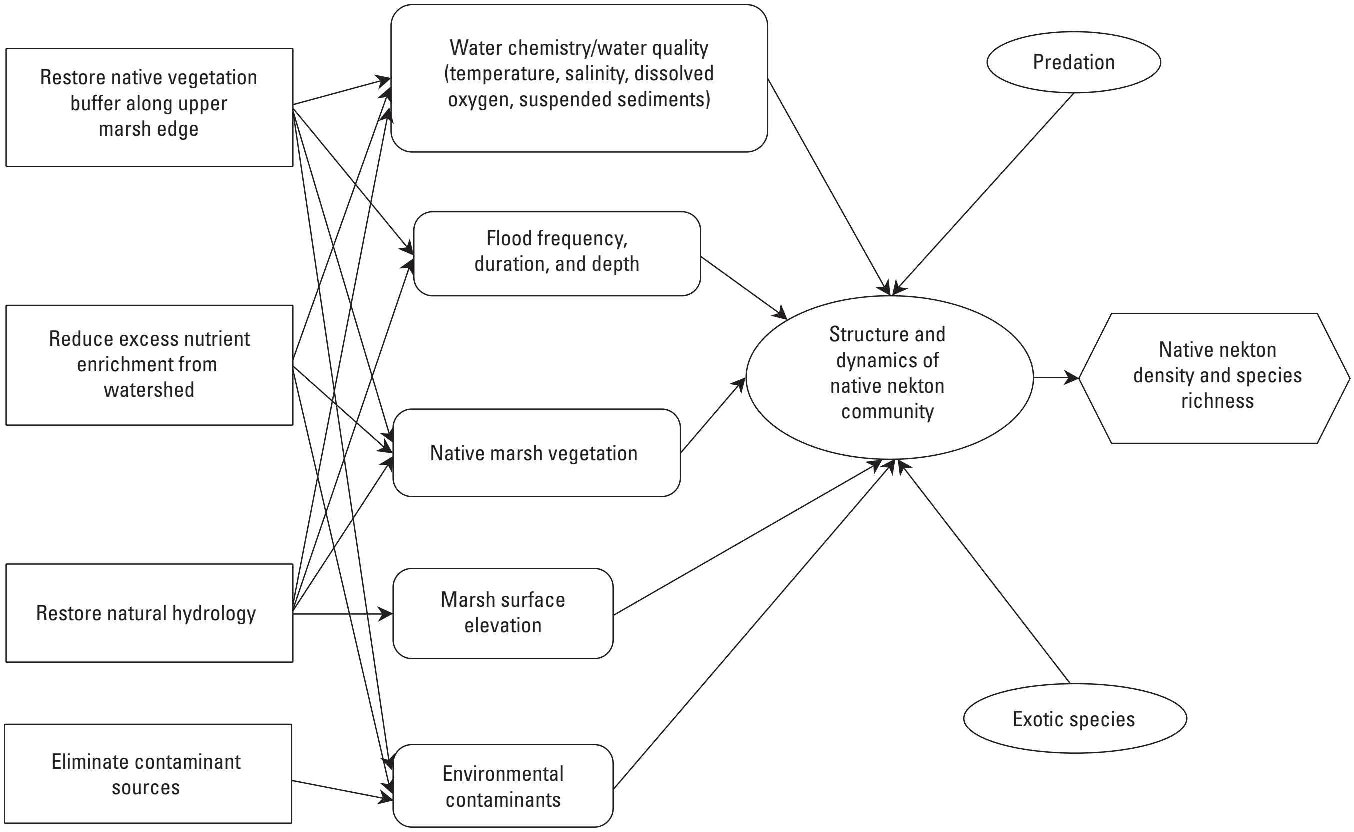

**Figure 1.2.** Influence diagram used to estimate nekton density and species richness in response to implementing certain management actions.

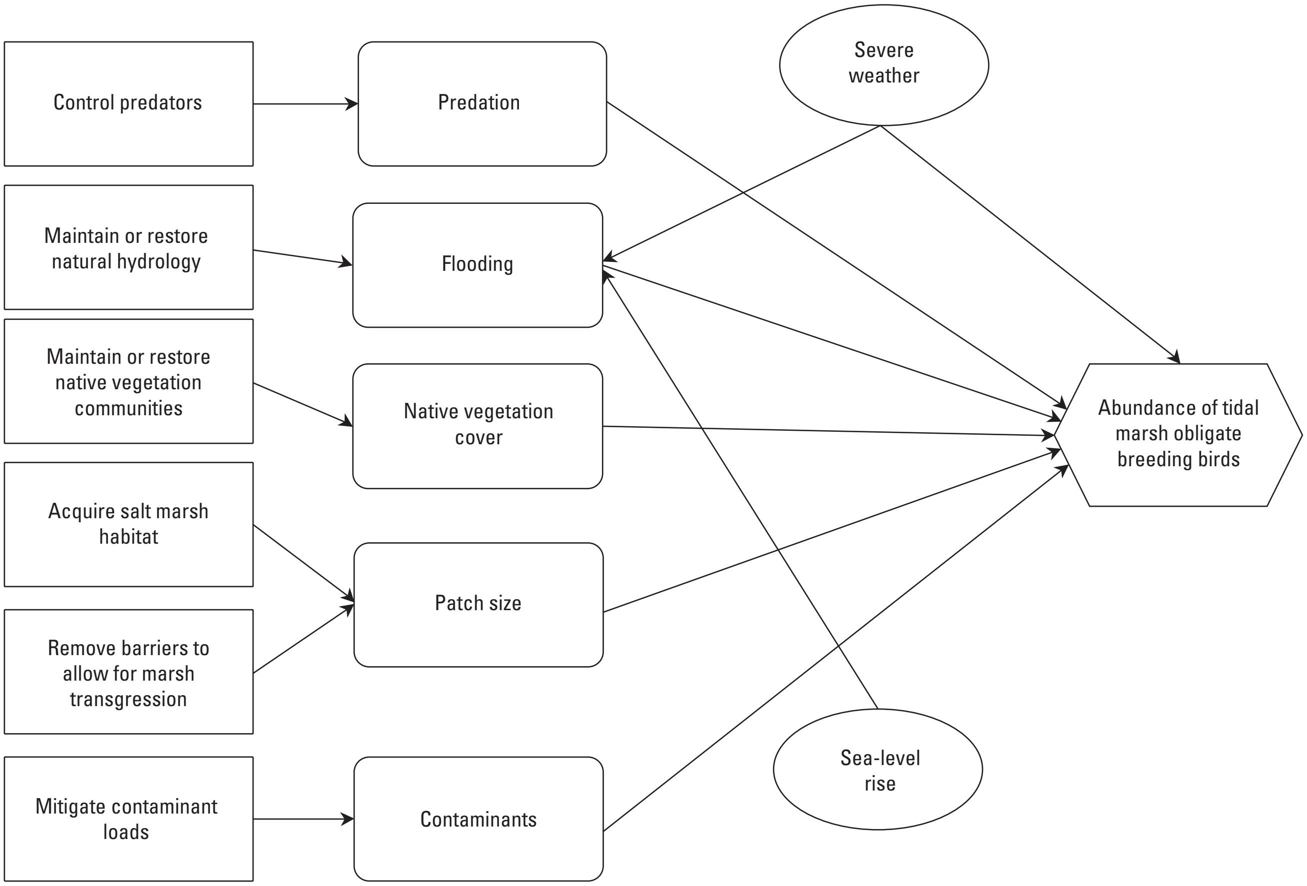

**Figure 1.3.** Influence diagram used to estimate abundance of tidal marsh obligate breeding birds in response to implementing certain management actions.

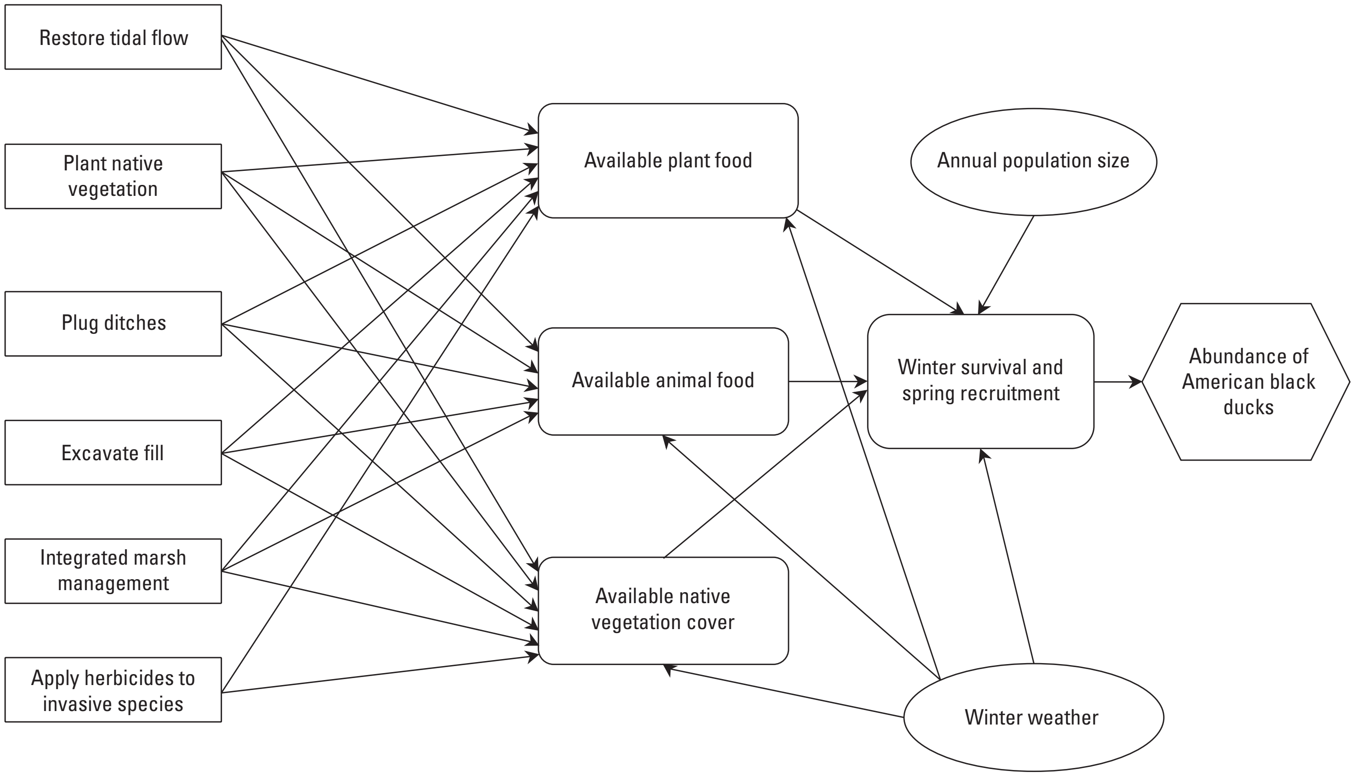

**Figure 1.4.** Influence diagram used to estimate abundance of American black ducks in winter, as indicator species for nonbreeding wetland birds, in response to implementing certain management actions.

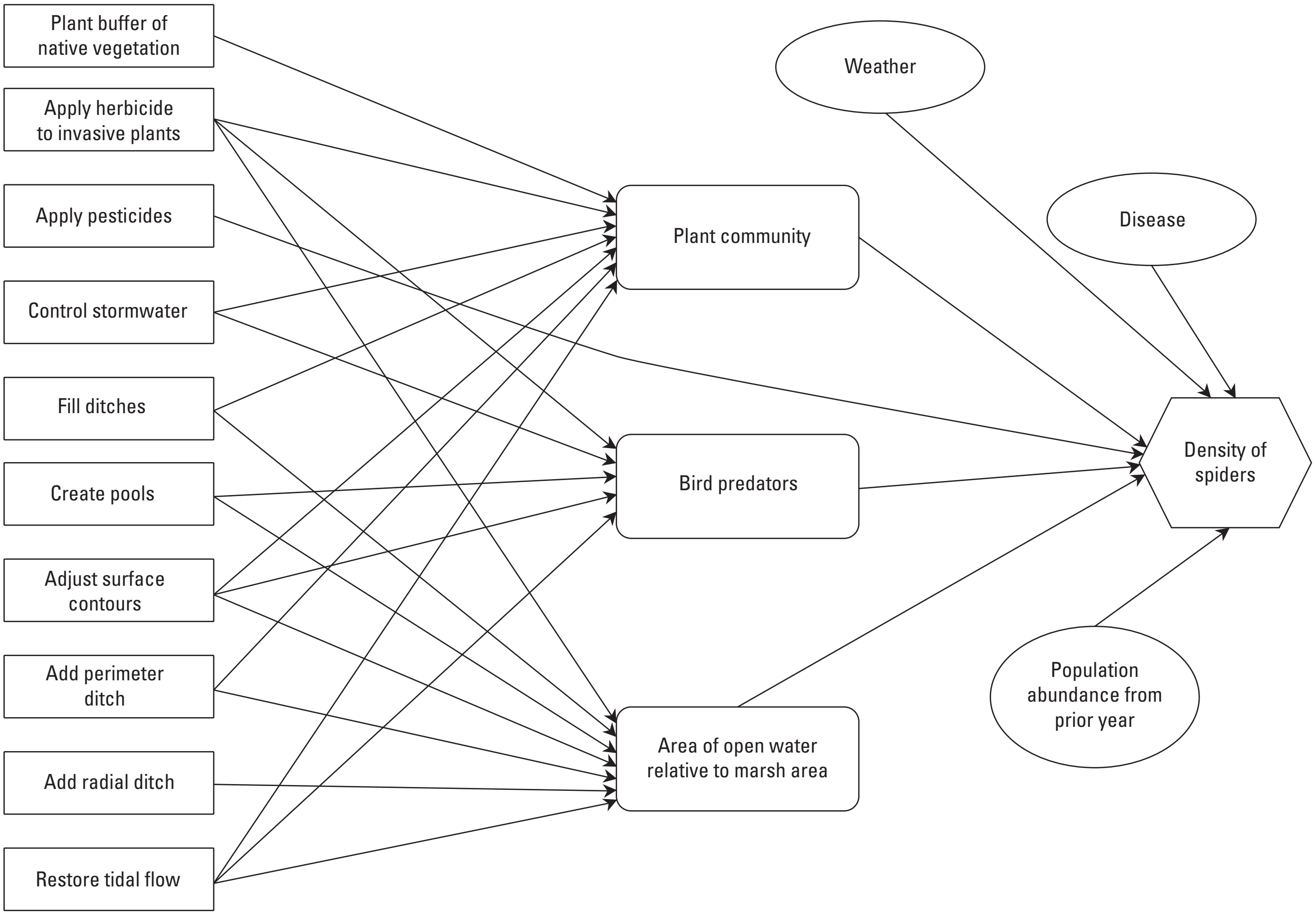

**Figure 1.5.** Influence diagram used to estimate density of spiders, as indicator of trophic health, in response to implementing certain management actions.

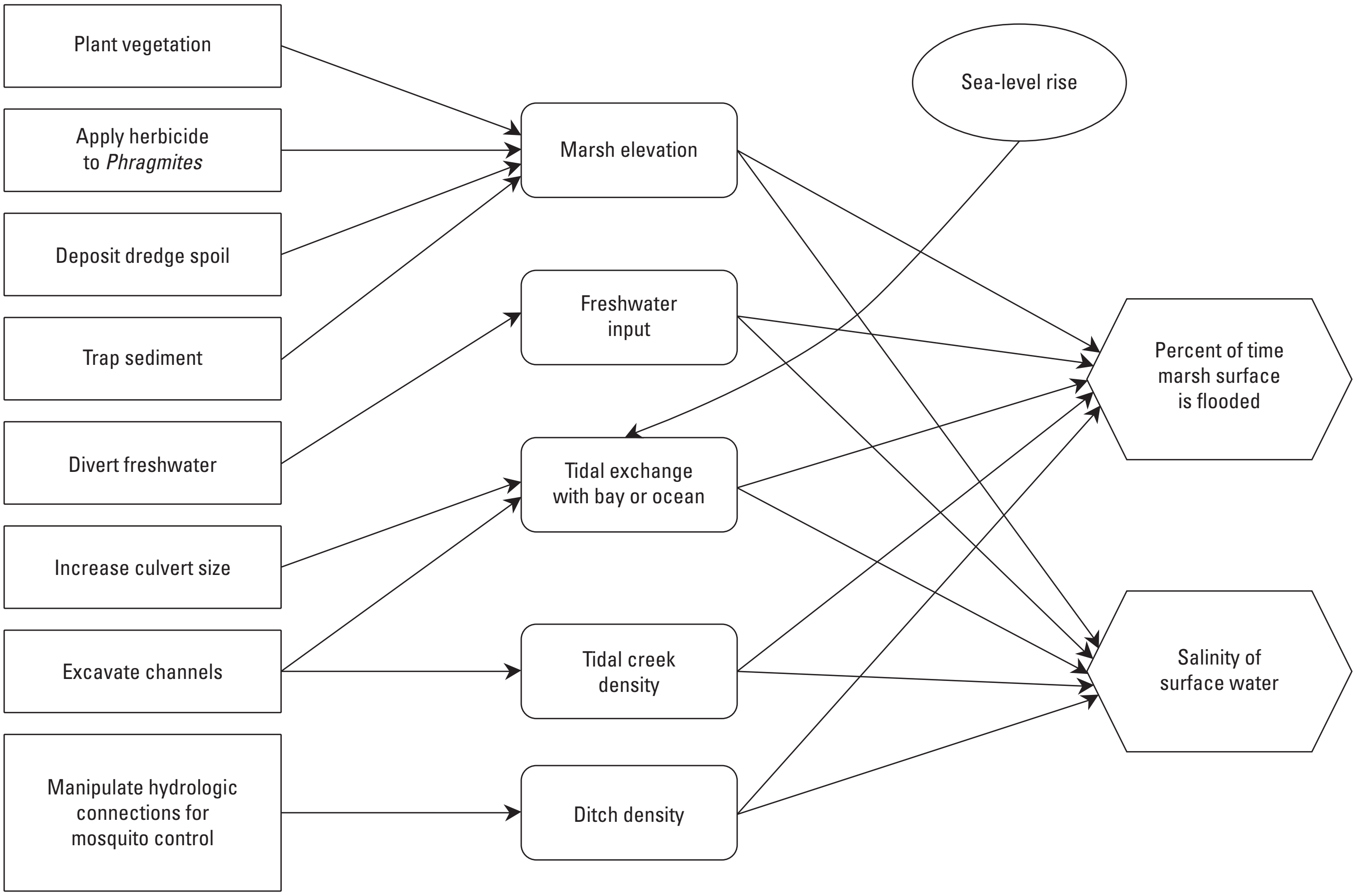

**Figure 1.6.** Influence diagram used to estimate percent of time marsh surface is flooded and salinity of marsh surface water in response to implementing certain management actions.

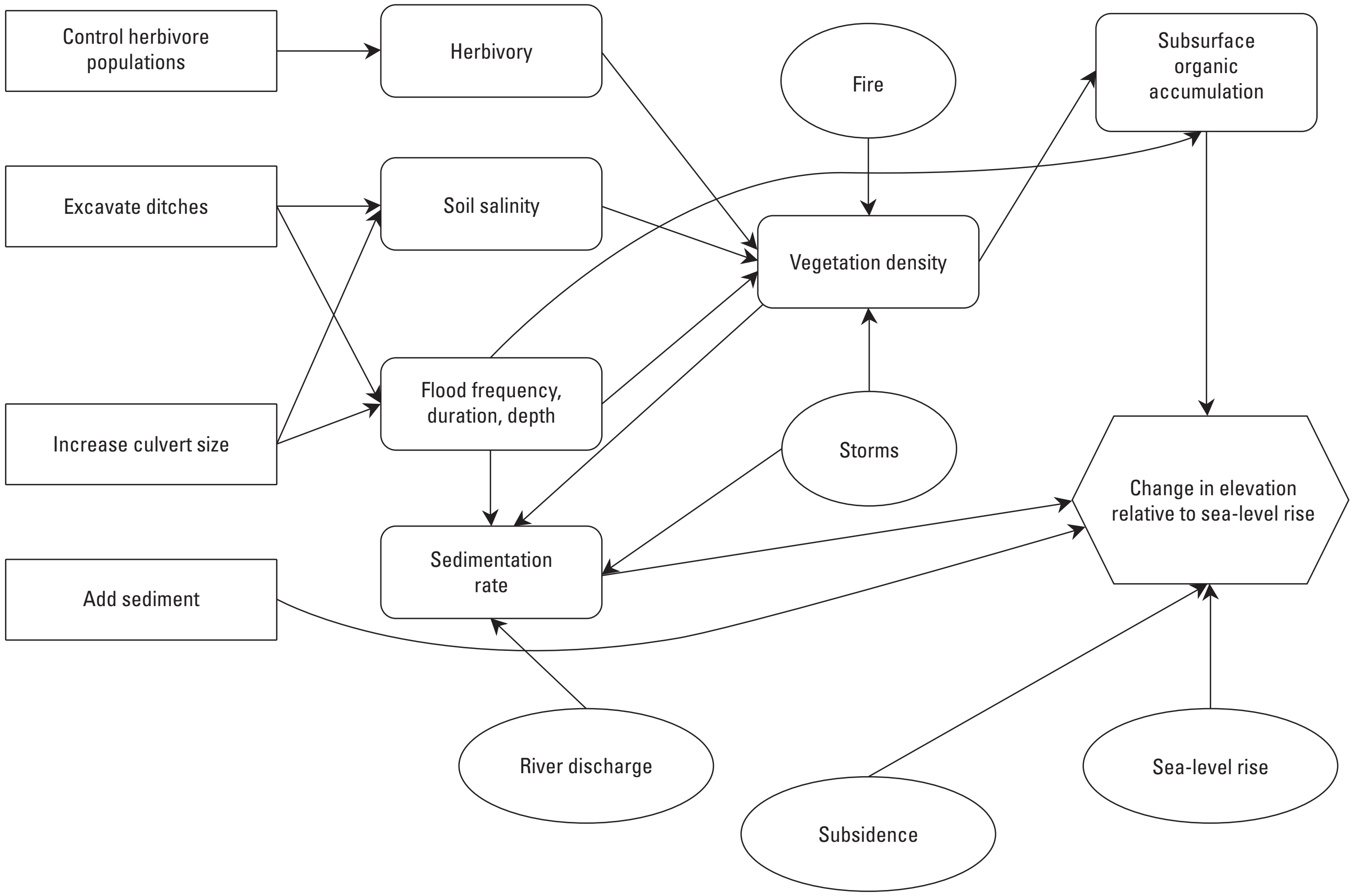

**Figure 1.7.** Influence diagram used to estimate change in elevation of the marsh surface relative to sea-level rise in response to implementing certain management actions.

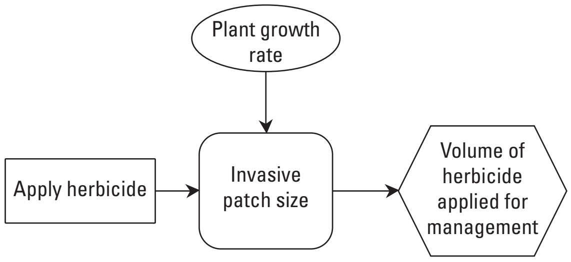

**Figure 1.8.** Influence diagram used to estimate volume of herbicide that would be applied if decision was made to use chemical control for removing unwanted vegetation.

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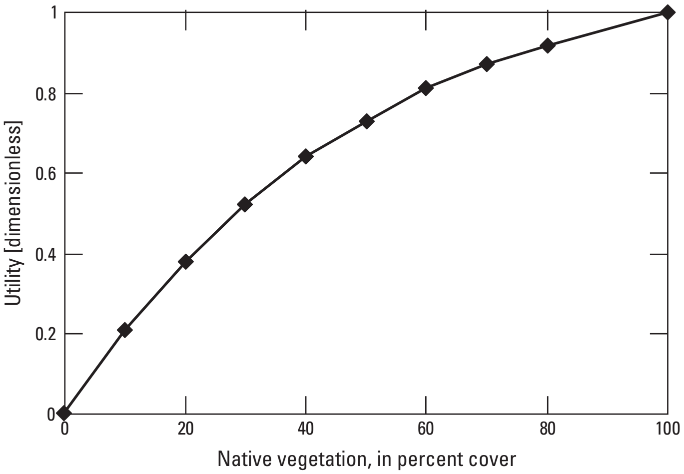
# Appendix 2. Utility Functions for the Stewart B. McKinney National Wildlife Refuge

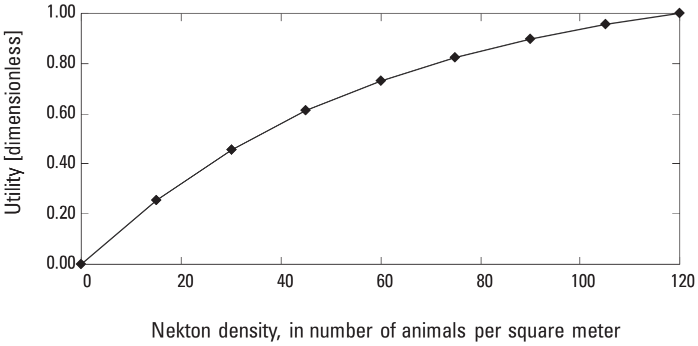
Utilities [$u(x)$] are derived as monotonically increasing, monotonically decreasing, or step functions over the range of performance metric $x$. In the functions in figures 2.1 through 2.10, $x$, *Low*, *High*, and $\rho$ are expressed in performance metric units; *Low* and *High* represent the endpoints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



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

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

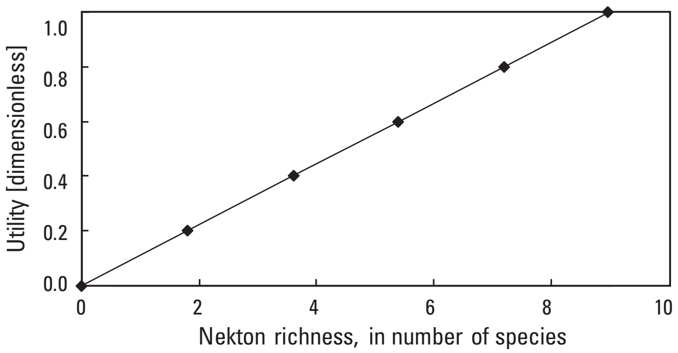
**Figure 2.1.** Native vegetation at the Stewart B. McKinney National Wildlife Refuge, Connecticut.



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

where
$Low = 0$
$High = 120$
$\rho = 60$

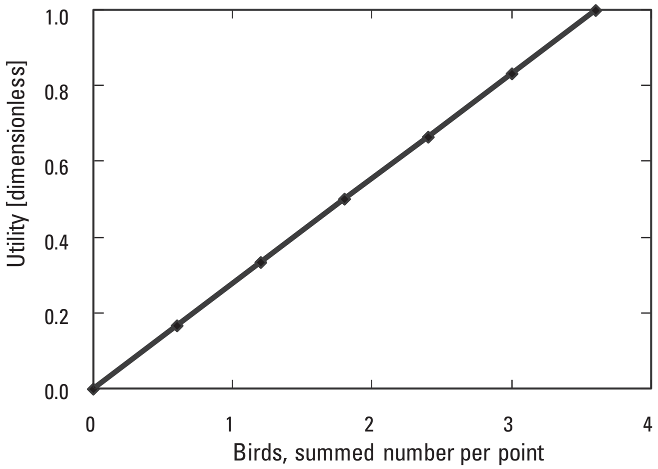
**Figure 2.2.** Native nekton density at the Stewart B. McKinney National Wildlife Refuge, Connecticut.



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

where
*Low* = 0
*High* = 9

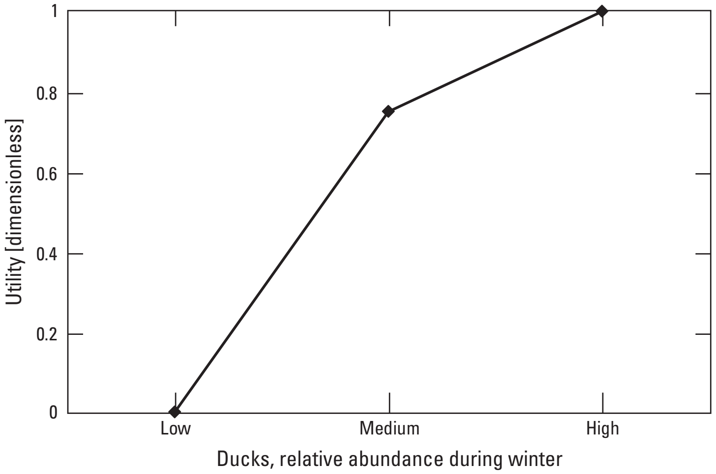
**Figure 2.3.** Native nekton species richness at the Stewart B. McKinney National Wildlife Refuge, Connecticut.



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

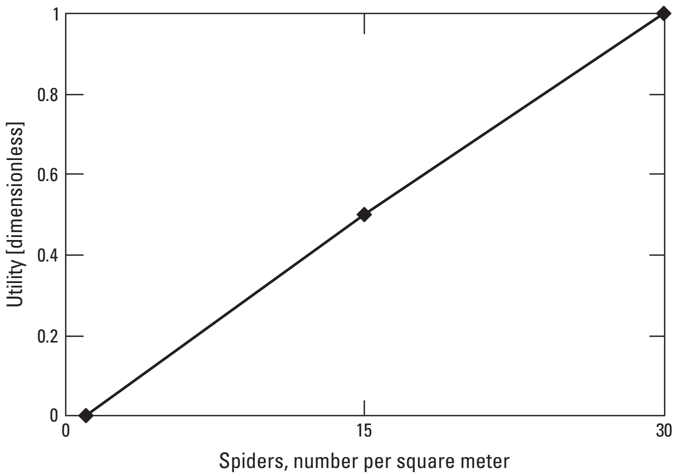
where
*Low* = 0
*High* = 3.6

**Figure 2.4.** Tidal marsh obligate birds at the Stewart B. McKinney National Wildlife Refuge, Connecticut.



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

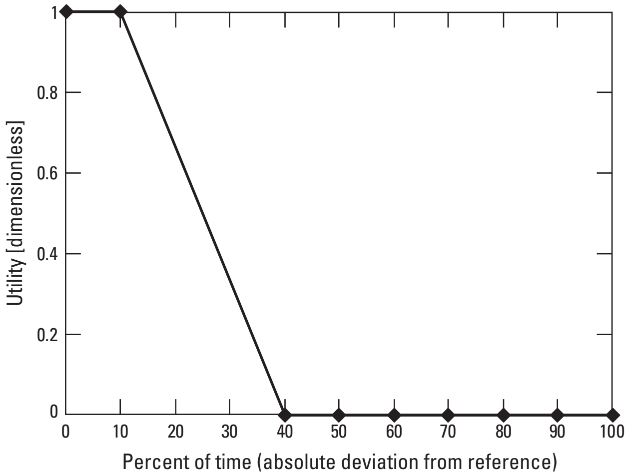
**Figure 2.5.** American black ducks at the Stewart B. McKinney National Wildlife Refuge, Connecticut.



If $x \le 15$, 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 Stewart B. McKinney National Wildlife Refuge, Connecticut.

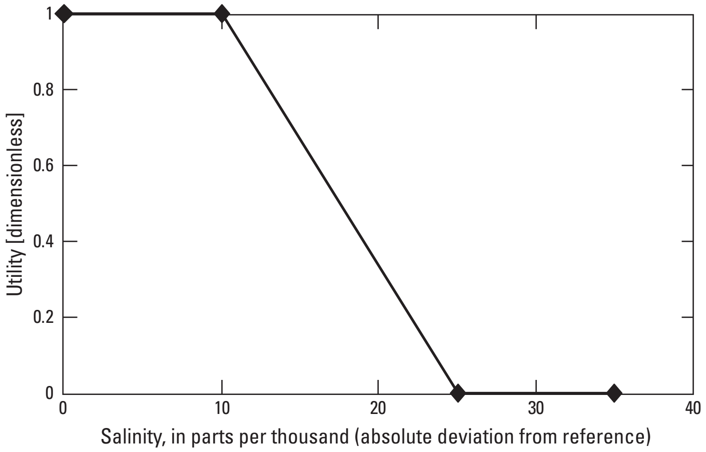


If $x \le 10$, then $u(x) = 1$

If $x \ge 40$, 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 Stewart B. McKinney National Wildlife Refuge, Connecticut.

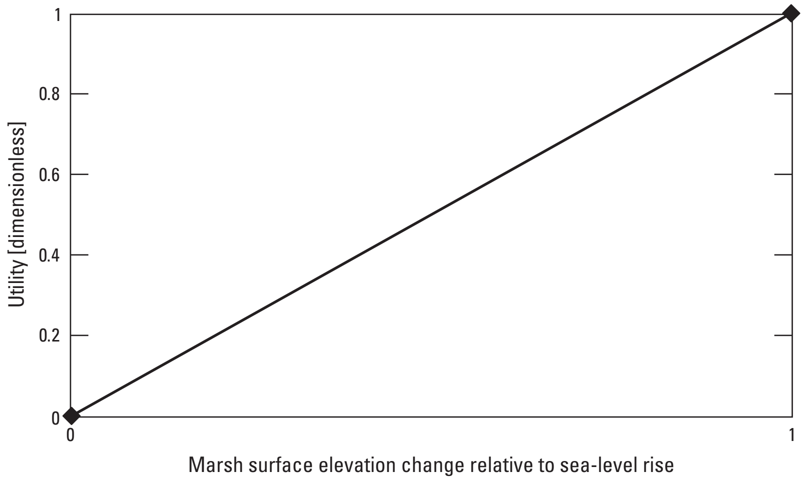


If $x \le 10$, then $u(x) = 1$

If $x \ge 25$, then $u(x) = 0$

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

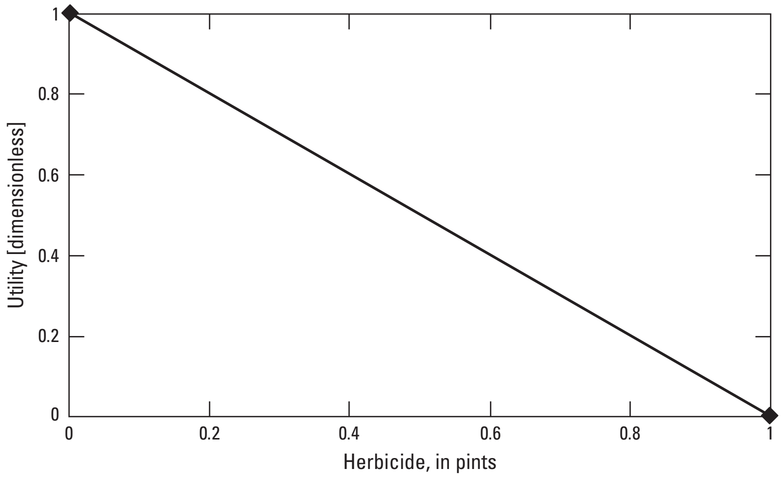
**Figure 2.8.** Salinity of surface water at the Stewart B. McKinney National Wildlife Refuge, Connecticut.



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

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 Stewart B. McKinney National Wildlife Refuge, Connecticut.



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

where
*Low* = 0
*High* = 1

**Figure 2.10.** Application of herbicides at the Stewart B. McKinney National Wildlife Refuge, Connecticut.

# Reference Cited

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