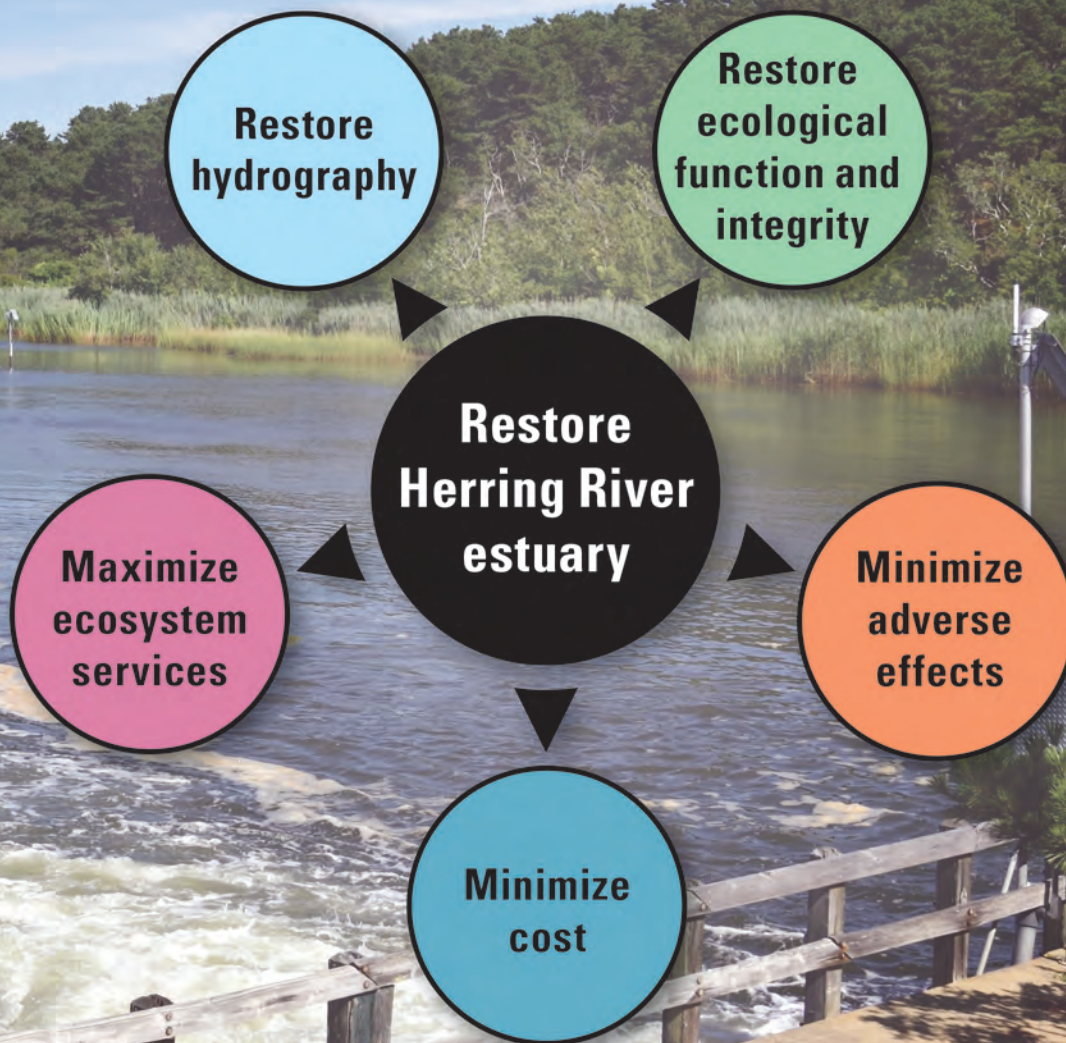


Prepared in cooperation with National Park Service and U.S. Fish and Wildlife Service

A Decision Framework to Analyze Tide-Gate Options for Restoration of the Herring River Estuary, Massachusetts



Open-File Report 2019–1115

Cover. (Front) Diagram showing fundamental objectives for the restoration of the Herring River estuary: restoration of the hydrography, restoration of the ecological function and integrity, minimization of adverse effects, maximization of ecosystem services, and minimization of management costs. (Back, top) Aerial view of the Chequessett Neck Road Dike. Image from Google Earth. (Back, bottom) Concept drawing of replacement dike with tide gates fully opened. Artwork by Nils Wiberg, Fuss & O'Neill, Inc. Background photo shows the Chequessett Neck Road Dike looking upstream. Photograph by Timothy P. Smith, National Park Service.

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By David R. Smith, Mitchell J. Eaton, Jill J. Gannon, Timothy P. Smith,
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Contents

Acknowledgments	iii
Abstract	1
Introduction.....	1
Study Area.....	2
Structuring the Decision Analysis	2
A Statement of the Problem	2
Definitions of the Objectives	4
Management Options	12
Prediction of Option Consequences	12
Evaluation of Tradeoffs	15
Implementation of an Option Through Time	15
Prototype Decision Analysis and Results	18
Next Steps.....	24
Summary.....	24
References Cited.....	25
Appendix 1. Conceptual Models	27
Appendix 2. Summary of Meeting with Herring River Restoration Committee to Elicit Utility Curves.....	32

Figures

1. Maps showing Herring River estuary and subbasins within Cape Cod National Seashore and towns of Wellfleet and Truro, Massachusetts.....	3
2. Objectives hierarchy showing the fundamental objectives and subobjectives for restoration of the hydrography, restoration of the ecological function and integrity, minimization of adverse effects, maximization of ecosystem services, and minimization of management costs	10
3. Graphs showing effects of alternative gate operations on mean high water for the Herring River estuary, Massachusetts.....	13
4. Example utility curves for selected objectives relating the level of a performance metric for hypothetical objectives to a standardized score between 0 and 1 based on preferences and risk attitude.....	18
5. Graph showing the four weighting schemes applied to the fundamental objectives to evaluate outcomes.....	20
6. Graph showing cumulative utility averaged across a range in prediction uncertainty and the four value-weighting schemes in figure 5 to compare seven tide-gate options in figure 3.....	21
7. Diagram showing frequencies of ranks based on cumulative utility after 25 years for seven options across a range in prediction uncertainty and the four value-weighting schemes in figure 5.....	21
8. Double-column chart used to evaluate how effectively the tide-gate options address all objectives	22
9. Graphs showing cumulative utility as a function of uncertainty formulated as the percentile for which confidence limits were computed for value weights: <i>A</i> , balanced, <i>B</i> , ecological, <i>C</i> , equal, and <i>D</i> , socioeconomic.....	23

Tables

1. Objectives of the Herring River estuary restoration decision support framework	5
2. The unweighted consequence table for the pilot tradeoff analysis	16
3. Overall utility from the pilot tradeoff analysis	19

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
Area		
acre	0.004047	square kilometer (km ²)
square mile (mi ²)	2.590	square kilometer (km ²)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

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.

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm²) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm³) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Abbreviations

CACO	Cape Code National Seashore
CNR	Chequesett Neck Road
CYCC	Chequesett Yacht and Country Club
DOI	U.S. Department of the Interior
EFDC	Environmental Flow Dynamics Code
GHG	Greenhouse gas
HREC	Herring River Executive Council
HRRC	Herring River Restoration Committee
MEM	Marsh Equilibrium Model
MHW	Mean high water
NPS	National Park Service
SLAMM	Sea Level Affecting Marsh Migration
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
T&E	Threatened and endangered
WBNERR	Waquoit Bay National Estuarine Research Reserve

A Decision Framework to Analyze Tide-Gate Options for Restoration of the Herring River Estuary, Massachusetts

David R. Smith¹, Mitchell J. Eaton², Jill J. Gannon³, Timothy P. Smith⁴, Eric L. Derleth³, Jonathan Katz⁵, Kirk F. Bosma⁶, and Elise Leduc⁶

Abstract

The collective set of decisions involved with the restoration of degraded wetlands is often more complex than considering only ecological responses and outcomes. Restoration is commonly driven by a complex interaction of social, economic, and ecological factors representing the mandate of resource stewards and the values of stakeholders. The authors worked with the Herring River Restoration Committee (HRRC) to develop a decision framework to understand the implications of complex tradeoffs and to guide decision making for the restoration of the 1,100-acre Herring River estuary within Cape Cod National Seashore, which has been restricted from tidal influence for more than 100 years. The HRRC represents decision maker and stakeholder interests in the restoration process. For a 25-year planning horizon, decisions involve the rate at which newly constructed water-control structures allow tidal exchange, and the timing and location of implementing numerous secondary management options. Decisions affect multiple stakeholders, including residents of two adjacent towns who value the watershed for numerous benefits and whose economy relies on seasonal activities and aquaculture. System response to management decisions is characterized by a high degree of uncertainty and risk with positive and negative outcomes possible. Decision policies will affect biophysical (for example, sediment transport, discharge of fecal coliform bacteria) and ecological (for example, vegetation response, fish passage, effects on shellfish) processes, as well as socioeconomic interests (for example, effects on property, viewsapes, recreation). The framework provides a structured approach for evaluating tradeoffs among multiple objectives (ecological and social) while appropriately characterizing relevant uncertainties and accounting for levels of risk

tolerances and the values of decision makers and stakeholders. Consequences of tide-gate management options are predicted using a range of methods from quantitative physical process models to elicited expert judgement. The decision framework is presented, and the software developed to implement the tradeoff analysis is introduced. The results from an initial prototype analysis using a software application developed for analyses of tradeoffs and of sensitivity of the decision to risk and uncertainty are presented. The next step is to use the decision-support application to analyze options using improved predictions.

Introduction

Ecological restoration is challenging, in part, because it is not only about ecological endpoints, but also about socioeconomic concerns. The motivations driving our will to restore affected systems are based on values, which are complex and vary widely among stakeholders. Therefore, the goal of restoring the ecological function of a salt marsh stands alongside the need to avoid or at least minimize the adverse effects to stakeholder interests. Stakeholders, who might be affected by the restoration or who might affect how the restoration proceeds, can have vastly different, and at times conflicting, interests. In addition, uncertainty in restoration outcomes and variation in attitudes about risk contribute to the challenge of restoration decision making. Thus, restoration success or failure can be determined by whether tradeoffs among multiple interests and risks associated with uncertain outcomes are suitably evaluated.

Decision analysis (Raiffa and others, 2002; Goodwin and Wright, 2014) is designed to evaluate tradeoffs and risks. Decision analysis examines the available strategies by first considering multiple interests in the outcome, based on the best available information for predicting the consequences of implementing one or more strategies. A large body of literature from management science, operations research, and engineering provides the foundation for decision analysis, which represents the “best management practices” for decision making, especially for complex problems and group decisions (Raiffa and others, 2002). Decision analysis takes a deliberative

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2 A Decision Framework to Analyze Tide-Gate Options for Restoration of the Herring River Estuary, Massachusetts

approach by providing options rather than advocating for a favored option. The process is transparent and explicit, can be documented, and is replicable, all of which can contribute to stakeholder acceptance of a decision. The decision analysis process guides decision makers towards a “good” decision that has the best chance of achieving the desired outcomes, while at the same time minimizing undesirable effects.

The tide gates at the Chequessett Neck Road (CNR) dike at the mouth of the Herring River (fig. 1) severely restrict tidal exchange and are the cause of severe ecological degradation to the estuary, which has been documented by on-site monitoring (Woods Hole Group, 2012; Cape Cod National Seashore and Herring River Restoration Committee, 2012). The degradation has motivated resource managers to pursue restoration of the Herring River estuary. Decision analysis is appropriate for exploring alternatives for the restoration of Herring River because (1) public resources are being used to support public decision making, (2) there is a variety of public and private interests at stake, (3) there is uncertainty about how the system will respond to restoration actions, and (4) restoration will take time thus providing the opportunity to adapt through a repeated cycle of prediction, decision making, and targeted monitoring.

To develop a decision analysis framework for evaluating tide-gate options for the restoration of Herring River estuary, the authors worked with the Herring River Restoration Committee (HRRC) to develop the decision framework through a series of meetings involving the committee and a workgroup formed for framework development. The HRRC represents decision maker and stakeholder interests in the restoration process. Workshops with stakeholders, science experts, and regulators helped those involved to better understand underlying issues, incorporate concerns and interests into the framework, and resolve technical questions. This report includes descriptions of the study area and the framework organized around the major decision components, followed by a discussion based on results from a prototype application of the decision framework.

Study Area

The 1,100-acre Herring River estuary lies within the towns of Wellfleet and Truro and partly within National Park Service (NPS) Cape Cod National Seashore (CACO) (fig. 1). The full Herring River restoration project area encompasses approximately 890 acres that would be affected by monthly spring high tide; 80 percent of this area falls under Federal stewardship within the CACO boundary, whereas 20 percent is outside the boundary in one of these two municipalities. The Herring River is the largest river system within the CACO and one of the largest tidally restricted estuaries on Cape Cod. The estuary has experienced more than 100 years of ecological degradation resulting from construction of the CNR dike and up-estuary drainage that began in 1909 and has resulted

in the almost complete exclusion of tidal exchange to most of the estuary. The CNR dike is outside the CACO boundary and is managed by the town of Wellfleet. The restoration area includes several tributary streams separated into nine sub-basins: Herring River (lower, mid, and upper), Mill Creek, Pole Dike Creek (lower and upper), Duck Harbor, and Bound Brook (lower and upper). The restoration project covers a large area encompassing public and private lands and structures, including a nine-hole golf course and an economically valuable oyster industry in Wellfleet Harbor.

Structuring the Decision Analysis

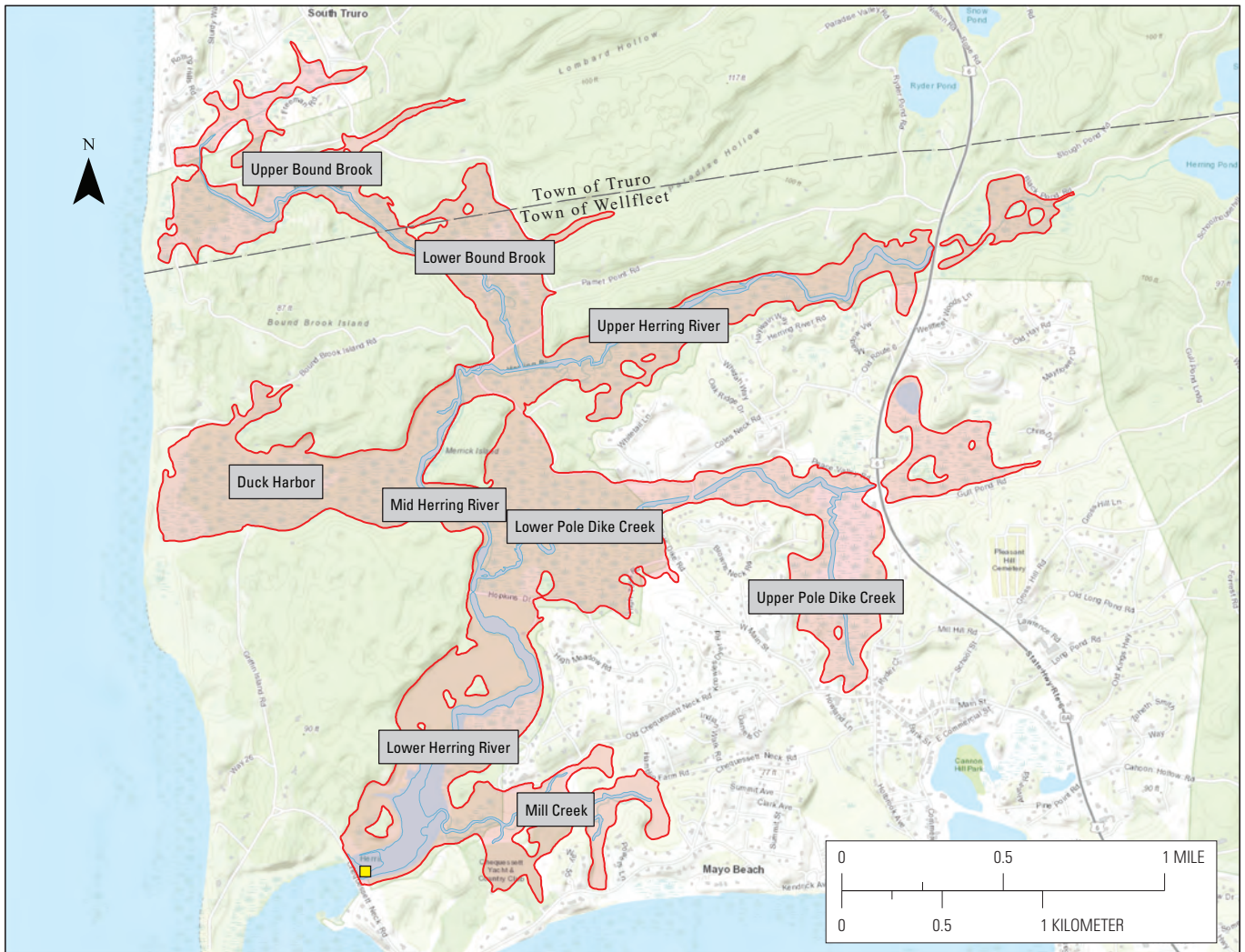
Raiffa and others (2002) and Hammond and others (2015) recognized the major components of decisions and developed a structured approach for implementation of decision analysis that involves defining the problem, specifying measurable objectives or interests, creating options or alternatives, predicting the consequences of these options relative to the objectives, and evaluating tradeoffs. The decision analysis for the Herring River restoration was structured according to six major components:

1. a clear statement of the problem,
2. comprehensive and measurable objectives,
3. a set of discrete tide-gate options,
4. a means to predict outcomes,
5. a process to evaluate the implications of these outcomes, and
6. a plan for implementation of a tide-gate option over time.

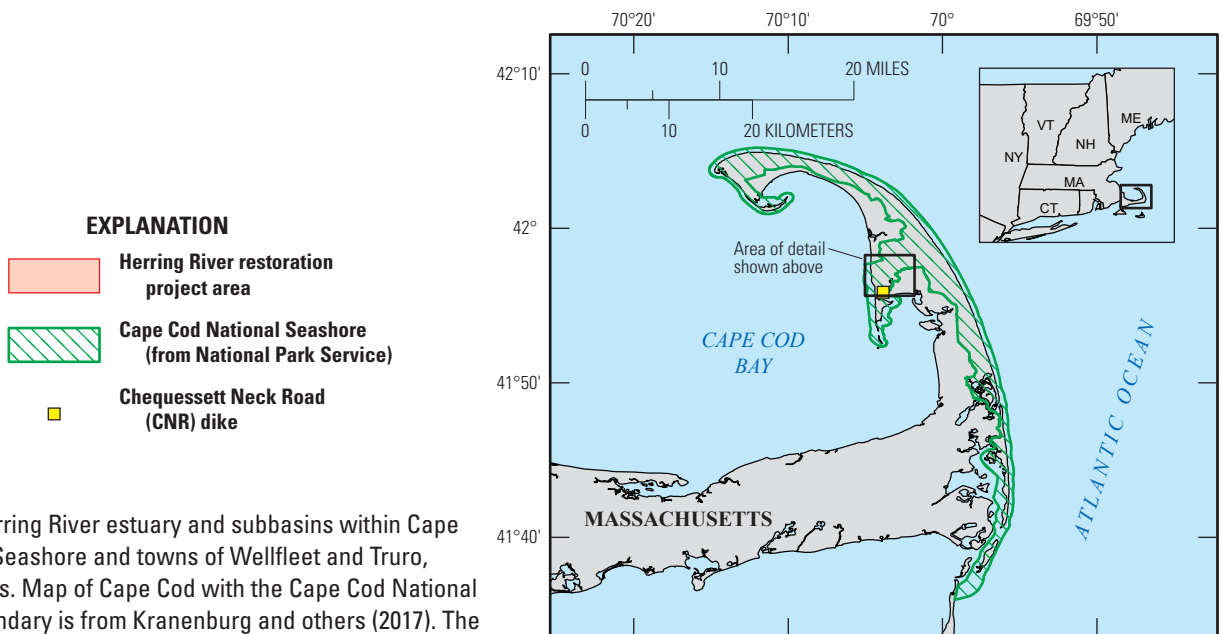
Monitoring will provide feedback to formally incorporate learning, reevaluate options, and possibly adapt management as restoration is implemented over time.

A Statement of the Problem

Representatives of Cape Cod National Seashore and the town of Wellfleet compose the Herring River Executive Council (HREC) and are responsible for restoring the Herring River estuary and minimizing adverse effects over some finite length of time (likely less than 25 years). The HREC will have ultimate responsibility for managing the new tide control gates at CNR, Mill Creek, and Pole Dike Creek and for implementing secondary management actions to achieve overall restoration goals. The HREC will receive decision recommendations from the HRRC, whose members are scientific and technical experts. The HREC will manage, directly or through contract, the project and implement gate operations and secondary management actions.



Base from Esri, 2014



Base from National Oceanic and Atmospheric Administration

EXPLANATION

- Herring River restoration project area
- Cape Cod National Seashore (from National Park Service)
- Chequessett Neck Road (CNR) dike

Figure 1. Herring River estuary and subbasins within Cape Cod National Seashore and towns of Wellfleet and Truro, Massachusetts. Map of Cape Cod with the Cape Cod National Seashore boundary is from Kranenburg and others (2017). The base layers for the top map and state boundary insert are the intellectual property of Esri and is used herein under license. Copyright © 2014 Esri and its licensors; all rights reserved.

Broadly, project goals are to restore the natural hydrography (that is, tidal range and marsh surface elevation) and ecological integrity of the Herring River estuary, while minimizing adverse economic and social effects, maximizing the estuary's production of ecosystem services, and minimizing management costs. The primary management actions adjust the volume of tidal flow through of a series of to-be-constructed tide gates at CNR, Mill Creek, and Pole Dike Creek; these actions require decisions on the number, location, magnitude of opening, and flow direction of the individual tide-gate openings at any given time. Timing and frequency of gate operations can be periodic or episodic; for example, gate opening can coincide with extreme high tides and storm events to facilitate movement of sediment farther upstream into the estuary. At each decision point, for example annually, gates can be configured to allow a greater, lesser, or the same volume of tidal flux into the estuary. In addition, project options include secondary management actions intended to accelerate the recovery of the estuarine habitat, enhance the benefits of tidal restoration achieved through tide-gate management alone, and reduce potential adverse ecological and socioeconomic effects of restoring tidal flow. Examples of secondary actions include management of floodplain vegetation (for example, vegetation removal or planting), modification of marsh surface elevations through management of sediment supply and distribution, and restoration of connectivity and natural sinuosity of tidal creeks to enhance the circulation of saltwater through the system. Decisions regarding secondary actions involve where and when to implement management measures, what techniques to use, and how to coordinate the actions with the tide-gate management.

The operational phase of tide-gate management encompasses the period of time when tidal flow increases until the gates are fully open and the maximum tidal range has been reached. Tide-gate management will cease after the gates are fully open, which is expected to take 25 years or less. The rate at which gates are opened varies among alternatives. In general, tide-gate management during the operational phase could occur 2–3 times a year and could be affected by season or tidal cycle. Secondary actions may be implemented before, during, and after the period of tide-gate management. Decisions involving management of the tide gates can be spatially and temporally divided by the subbasins within the project area. Tide-gate management decisions will begin as soon as construction of the tide-control structures is complete. Decisions regarding secondary actions may range from simple and independent of other decisions to complex and linked to other management actions requiring coordination with the tide-gate management. For example, removal of vegetation may be beneficial to occur prior to restoration of tidal exchange for logistical purposes or to minimize effects on the flood plain.

Tide-gate management decisions and secondary action decisions will be made (1) based on predicted outcomes of available actions with respect to the multiple project objectives and (2) given the uncertainty in system response to the actions taken. In general, varying degrees of uncertainty revolve around changes in tidal regime and salinity under different

tide-gate configurations and changes to vegetation, water quality, sediment distribution, and other processes resulting from modifications to the hydrodynamics.

Decisions about tide-gate adjustments are subject to regulatory oversight under the U.S. Clean Water Act [33 U.S.C. §1251 et seq. (1971)], the Massachusetts Wetlands Protection Act (General Laws of Massachusetts Chapter 131, §40) and Waterways Regulations (310 CMR 9.00), the Town of Wellfleet wetland by-laws, and the Massachusetts Endangered Species Act (321 CMR 10.00). Tide-gate decisions will be constrained by the management actions required to protect public and private structures and property within the project area.

Definitions of the Objectives

Defining the objectives starts with the issues decision makers and stakeholders care about, what they want to achieve, and what they want to avoid (Gregory and Keeney, 2002; McGowan and others, 2015). For Herring River estuary restoration, the focus is on achieving ecological and socioeconomic objectives. When the objectives are expressed as measurable attributes, the relative achievements of management alternatives can be compared to identify the option that best meets the objectives (Keeney and Gregory, 2005). Because achieving value for some objectives may come at the cost of other objectives, a formalized approach for evaluating tradeoffs among these objectives is often required. The manner in which the objectives are weighted in that comparison is part of the tradeoff analysis discussed below. The fundamental and highest-level objectives for Herring River restoration are to restore the hydrography, ecological function, and integrity of the estuary; minimize adverse effects on the local ecosystem, adjacent landowners, and other stakeholders; maximize production of ecosystem services; and minimize management costs (table 1, fig. 2). The fundamental objectives are further defined by subobjectives. Each subobjective has a performance measure, which serves two purposes. They provide a quantitative metric by which (1) predictions are made to evaluate how well an alternative is expected to meet each of the objectives and (2) observations will be made through monitoring to determine the progress towards achieving the objectives once an action has been implemented.

In addition, a set of objectives has been specified that has to do with strategic goals or the underlying process of how decisions are made, implemented, and communicated. Examples include maximize long-term collaboration of the partnership, maximize access to funding opportunities, maximize responsiveness to community concerns, maximize public awareness and support for the project, and maximize learning about ecological restoration. While these objectives are important, they would not be useful in a tradeoff analysis to distinguish among different options for gate operation or secondary management actions. In other words, process and strategic objectives are intended to be met equally, regardless of management options, and therefore are not included when a tide-gate option is analytically selected.

Table 1. Objectives of the Herring River estuary restoration decision support framework. There are five fundamental objectives with subobjectives within each fundamental objective. Each subobjective is accompanied by the performance measure (that is, metric) to be used to measure the current state of the objective, the method to be used to predict the objective of a given tide-gate management option, and the method to be used to monitor the objective after implementation of the option.

[EFDC, Environmental Fluid Dynamics Code; MEM, Marsh Equilibrium Model; SLAMM, Sea Level Affecting Marsh Model; WBNERR, Waquoit Bay National Estuarine Research Reserve; GHG, Greenhouse Gas; DO, dissolved oxygen; TBD, to be determined; MHW, mean high water; CNR, Chequessett Neck Road ; CYCC, Chequessett Yacht and Country Club; T&E, threatened & endangered; h, hour; mg/L, milligram per liter; meTonsC/ha/yr, metric tons of carbon per hectare per year; ft, foot; %, percent, mm, millimeter; psu, practical salinity units; <, less than; >, greater than; >=, greater than or equal to; USGS, U.S. Geological Survey]

Subobjectives	Performance measure	Desired direction	Spatial scale	Prediction method	Monitoring	
Fundamental Objective #1: Restore Hydrography						
Restore tidal range	Low tide	Minimum water surface elevations (ft) averaged for subbasins and at key locations	Minimize	Subbasin	EFDC Hydrodynamic Model	Electronic water-level data loggers for subbasins and at key locations
	High tide	Maximum water surface elevations (ft) averaged for subbasins and at key locations	Maximize	Subbasin	EFDC Hydrodynamic Model	Electronic water-level data loggers for subbasins and at key locations
Restore hydroperiod	Flooding extent	Marsh area inundated by tides (%)	Maximize	Subbasin	EFDC Hydrodynamic Model	Electronic water-level data loggers for subbasins and at key locations
	Duration of flooding	Duration (h) of inundation of marsh surface at key locations	Maximize	Subbasin	EFDC Hydrodynamic Model	Electronic water-level data loggers for subbasins and at key locations
Maximize marsh surface drainage	Extent of ponded water at low tide (%)	Minimize	Subbasin	EFDC Hydrodynamic Model	Electronic water-level data loggers in areas of predicted ponding	
Maximize marsh surface elevation	Marsh surface sediment deposition	Accumulation of sediment at key marsh surface locations (mm)	Maximize	Subbasin	EFDC Hydrodynamic Model with Sediment Module, linked with MEM	Deposition/Elevation at surface elevation tables and markers
	Below surface accretion (shallow subsidence)	Surface elevation (mm)	Maximize	Lower Herring Basin	Baseline data; Published values; Input from SLAMM Model; Expert judgment/elicitation	Soil sampling associated with marsh surface elevation monitoring sites

6 A Decision Framework to Analyze Tide-Gate Options for Restoration of the Herring River Estuary, Massachusetts

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Subobjectives	Performance measure	Desired direction	Spatial scale	Prediction method	Monitoring	
Fundamental Objective #2: Restore Ecological Function/Integrity						
Maximize area restored	Appropriate salinity gradient	<ul style="list-style-type: none"> • <5 • 5 to 18 • >18 	Optimize	Estuary	EFDC Hydrodynamic Model	Conductivity data loggers for subbasins and at key locations
	Coverage of emergent vegetation	Area of emergent vegetation with psu <ul style="list-style-type: none"> • <5 • 5 to 18 • >18 	Maximize	Estuary	EFDC (salinity model results) coupled with SLAMM wetland-type results	Transect/Plot cover estimates; Habitat mapping
Surface-water quality	pH	% of samples with pH < 5	Minimize	Lower Herring Basin	Expert elicitation informed by EFDC Hydrodynamic Model and USGS model	Continuous surface-water-quality monitoring at key locations
	DO	% of samples with DO < 5	Minimize	Lower Herring Basin	Expert elicitation informed by EFDC Hydrodynamic Model and USGS model	Continuous surface-water-quality monitoring at key locations
Habitat quality for estuarine community	Species composition of benthic invertebrate community (similarity index 0-1)	Maximize	Estuary	Published values; expert elicitation informed by EFDC Hydrodynamic Model	Benthic sampling at key locations	
Maximize connectivity for Diadromous fish	Fish passage indicated by fish counts	Maximize	Estuary	Expert elicitation informed by EFDC predictions of flow velocity at culverts/crossings and current and historical fish counts	Fish counts at crossings	

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Subobjectives	Performance measure	Desired direction	Spatial scale	Prediction method	Monitoring
Fundamental Objective #3: Minimize Adverse Effects					
Prevent effects on wells, property, structures, and roads	Number of wells, structures, or roads affected	Minimize	Estuary	Water-surface elevation output from EFDC Hydrodynamic Model	Electronic water-level data loggers for subbasins and at key locations
Minimize risk to public safety	Risk to public at water control structures	Minimize	Estuary	Calculated from gate configuration (number of gates at specified heights)	Observations of activity during peak-use periods
	Risk to public elsewhere	Minimize	Estuary	Calculated from gate configuration and average depth per subbasin at MHW	Observations of activity during peak-use periods
Prevent adverse effects on shellfish beds in harbor	Ammonium export	Minimize	Wellfleet Harbor	Expert elicitation based on EFDC predictions of residence time, hydroperiod, and water surface elevation above saturated peat	Surface-water-quality monitoring near aquaculture areas
	Fecal coliform levels	Minimize	Wellfleet Harbor	Expert elicitation based on EFDC predictions of Residence Time	Surface-water-quality monitoring near aquaculture areas
	Sediment deposition onto shellfish beds	Minimize	Wellfleet Harbor	Expert elicitation informed by EFDC	Total suspended solids downstream from dike; particle size & deposition near aquaculture areas

8 A Decision Framework to Analyze Tide-Gate Options for Restoration of the Herring River Estuary, Massachusetts

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Subobjectives	Performance measure	Desired direction	Spatial scale	Prediction method	Monitoring	
Fundamental Objective #3: Minimize Adverse Effects—Continued						
Public satisfaction	Loss of privacy for abutters	Number of complaints	Minimize	Estuary	Expert elicitation based on EFDC predictions of water surface elevation and salinity, and on predictions of vegetation change	Documentation of incidents
	Public viewscapes	% of visual field that looks bad from key locations and visible presence of machinery during tourist season	Minimize	Estuary	SLAMM coupled with ArcMap viewshed analysis and expert elicitation	Time series photo stations and documentation of incidents
	Appearance of dead woody vegetation	% of visual field that looks bad from private property	Minimize	Estuary	SLAMM coupled with ArcMap viewshed analysis	Time series photo stations
	Smell	Number of complaints	Minimize	Estuary	Expert judgment/elicitation	Documentation of complaints
	Community conflict	Likelihood of litigation (%)	Minimize	Estuary	Expert judgment/elicitation	Documentation of conflicts and resolutions

Table 1. Objectives of the Herring River estuary restoration decision support framework. There are five fundamental objectives with subobjectives within each fundamental objective. Each subobjective is accompanied by the performance measure (that is, metric) to be used to measure the current state of the objective, the method to be used to predict the objective of a given tide-gate management option, and the method to be used to monitor the objective after implementation of the option.—Continued

[EFDC, Environmental Fluid Dynamics Code; MEM, Marsh Equilibrium Model; SLAMM, Sea Level Affecting Marsh Model; WBNERR, Waquoit Bay National Estuarine Research Reserve; GHG, Greenhouse Gas; DO, dissolved oxygen; TBD, to be determined; MHW, mean high water; CNR, Chequesett Neck Road ; CYCC, Chequesett Yacht and Country Club; T&E, threatened & endangered; h, hour; mg/L, milligram per liter; meTonsCe/ha/yr, metric tons of carbon per hectare per year; ft, foot; %, percent, mm, millimeter; psu, practical salinity units; <, less than; >, greater than; >=, greater than or equal to; USGS, U.S. Geological Survey]

Subobjectives	Performance measure	Desired direction	Spatial scale	Prediction method	Monitoring
Fundamental Objective #4: Maximize Ecosystem Services					
Climate change mitigation	Biomass carbon storage (meTonsCe/ha/yr)	Maximize	Estuary	WBNERR GHG calculator informed by EFDC Hydrodynamic Model output	Atmospheric carbon exchange; Soil carbon accumulation
Shellfishing opportunities	Area of available habitat (acres) and likelihood of closures not exceeding current number of closures	Maximize	Above and below CNR dike	EFDC Hydrodynamic Model and expert elicitation	Fecal coliform counts and documentation of incidences
Natural mosquito control	Mosquito species composition and abundance	TBD	TBD	Expert elicitation based on EFDC output for ponding and salinity	Larvae counts in breeding areas
Maximize recreational opportunities	Loss of golfing opportunities at CYCC	Minimize	CYCC	Expert elicitation	Documentation of incidences
	Loss of existing recreational opportunities	Minimize	Estuary	Expert elicitation [based on EFDC predictions of area flooded]	Documentation of loss/gain of access points
	Newly created recreational opportunities	Maximize	Estuary	Expert elicitation [based on EFDC predictions of area flooded]	Car counts; User surveys; Observations of activity during peak-use periods
Fundamental Objective #5: Minimize Cost					
Minimize cost for secondary actions	Cost for secondary actions	Minimize	Estuary	Expert judgment/elicitation	Project timeline/ Financial records
Minimize cost for tide-gate operations	Cost for tide-gate operations	Minimize	Estuary	Expert judgment/elicitation	Project timeline/ Financial records
Minimize cost for monitoring	Cost for monitoring	Minimize	Estuary	Expert judgment/elicitation	Project timeline/ Financial records
T&E Monitoring	Probability that permit requirements fully met	Maximize	Estuary	Expert judgment/elicitation	Documentation as required by permit

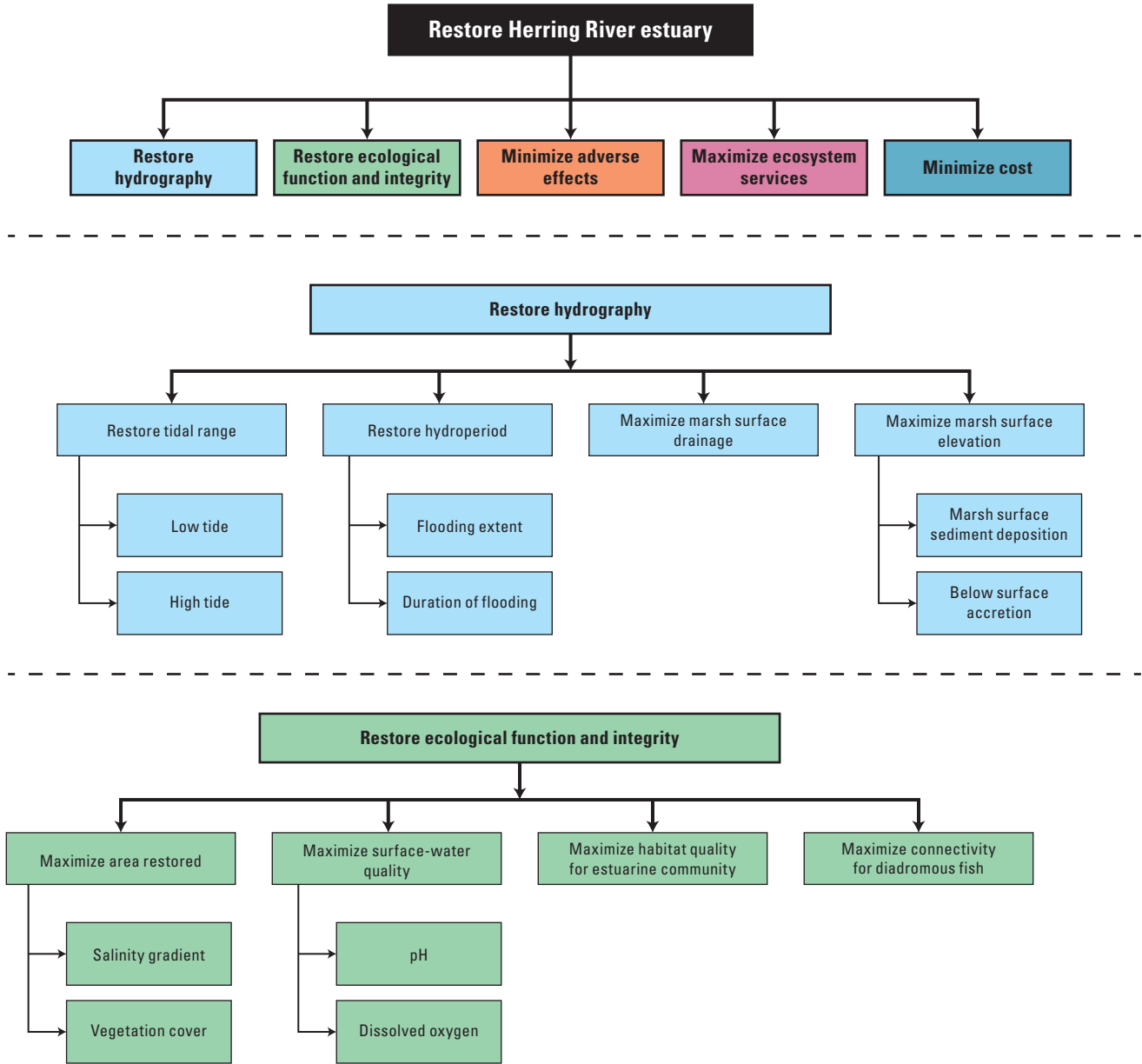


Figure 2. Fundamental objectives and subobjectives for restoration of the hydrography, restoration of the ecological function and integrity, minimization of adverse effects, maximization of ecosystem services, and minimization of management costs. (CYCC, Chequessett Yacht & Country Club)

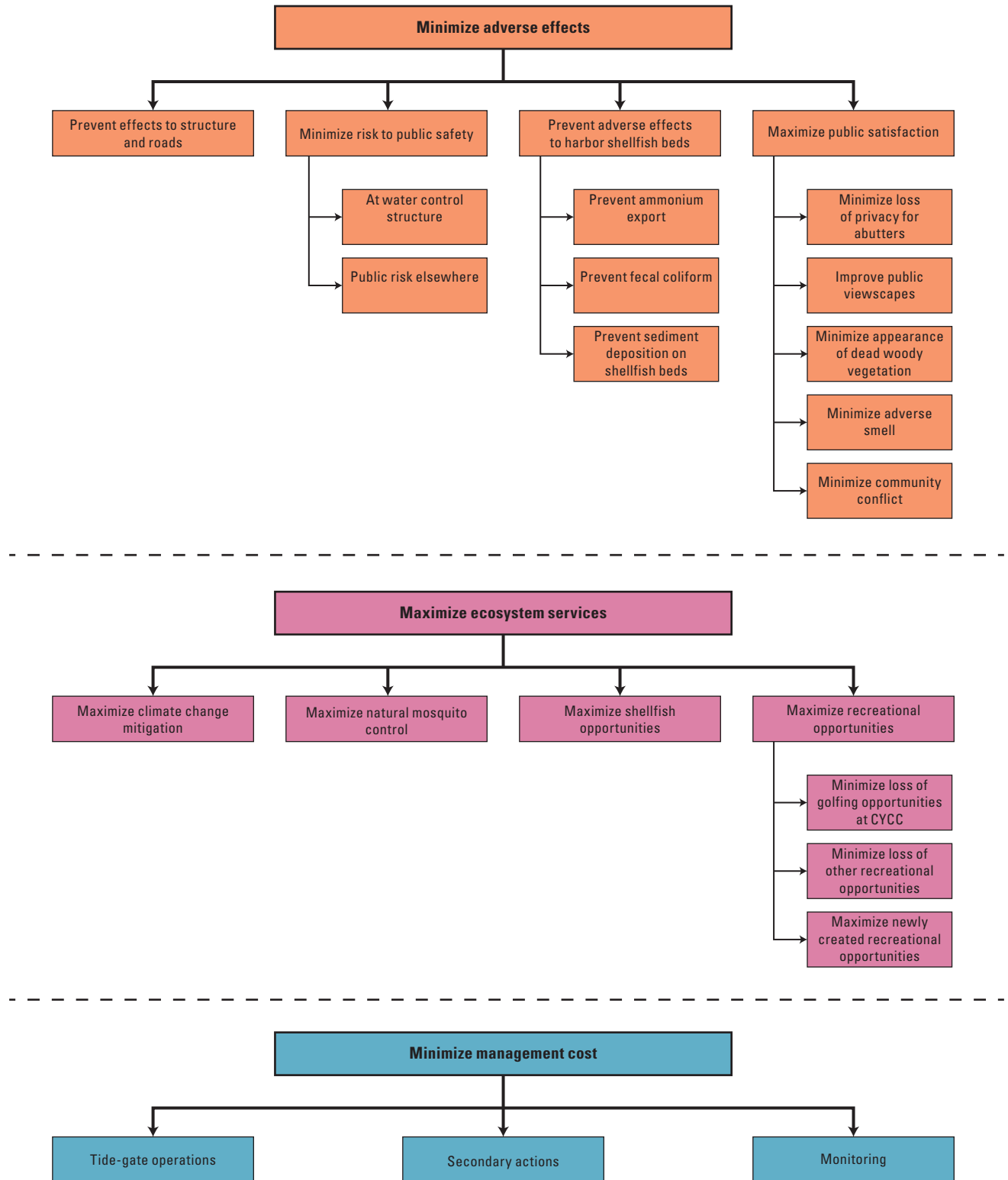


Figure 2. Fundamental objectives and subobjectives for restoration of the hydrography, restoration of the ecological function and integrity, minimization of adverse effects, maximization of ecosystem services, and minimization of management costs. (CYCC, Chequessett Yacht & Country Club)—Continued

Management Options

For restoration of the Herring River estuary, there are two broad categories of actions: tide-gate management and secondary management actions designed to affect the estuary by a means other than tidal exchange, such as, mechanical removal of woody vegetation within a subbasin. Thus, the term “option” denotes a set of actions, including tide-gate management or secondary actions, implemented over time. The terms “alternatives” and “options” are used synonymously in this report.

Options for tide-gate management at the CNR dike are defined by the pace of restoring tidal range (fig. 3). Mean high water (MHW) in the Lower Herring River subbasin, expressed as feet above the North American Vertical Datum of 1988, is used to indicate progress towards restoration, and maximum MHW = 4.3 feet (ft) is expected to be reached within a 25-year period (Woods Hole Group, 2012). In contrast, Woods Hole Group (2012) found that MHW in the Lower Herring River subbasin is 0.37 ft. Options for tide-gate manipulations vary by the pace of reaching a benchmark tidal elevation (for example, slow then fast versus fast then slow) or are designed for special purposes, such as facilitating sediment deposition upstream or enhancing recovery of estuarine vegetation communities. Each tide-gate option identifies a complete sequence of manipulations that would occur over time frames of up to 25 years.

These policies were developed to achieve full tidal flow by a certain time or to address specific hypotheses, objectives, or solutions. The 5-year, 15-year, and 25-year threshold options would open the tide gates at a constant rate so gates will be fully open by 5, 15, or 25 years, respectively (fig. 3A). Variations on these strictly time-based options are designed to be precautionary (that is, the 15-year Slow.Fast and the 15-year Fast.Slow options; fig. 3A), manage vegetation by means of tidal flow (that is, the Growing Season option; fig. 3B), or enhance upstream sediment transport and deposition (that is, the Sediment option; fig. 3C). The 15-year Slow.Fast option opens the gates slowly at first and then accelerates gate opening to fully open the gates by 15 years. In contrast, the 15-year Fast.Slow option initially opens the gates rapidly and then opens gates slowly thereafter to fully open the gates at 15 years. The Growing Season option opens gates in steps to kill invasive reeds (*Phragmites*) in the lower basin and pauses for a growing season to allow emergent native vegetation growth to capture sediment. The Sediment option opens gates periodically, closes gates on outgoing tides to allow sediment to settle, and then episodically opens the gates during incoming spring or storm tides to allow greater upstream sediment deposition.

For the purposes of planning, a management year of November–October was assumed, with the indicated gate changes occurring at the beginning of the specified year. The tide gates, and thus MHW, remain static for the full management year until the next time that a change is scheduled. The Sediment option, which periodically opens and closes gates

to promote sediment deposition (fig. 3C), anticipates a single peak occurring in November; however, there may be one or more peaks in the specified years that will occur with the highest predicted tide(s) of the year and (or) with an unpredictable storm event, which introduces some uncertainty into the within year timing of gate operation. Each peak will last four consecutive tidal cycles, centered around the high tide.

Tide-gate options are referred to as “platform” options because they provide the baseline conditions or platform upon which secondary actions will be added. Types of secondary management actions include vegetation management, sediment management, and channel and marsh surface management. Secondary actions are “added on top of” tide-gate management to meet particular objectives. The selection process is to identify the best performing tide-gate platform option, propose alternative secondary actions, and then select the best overall option (tide-gate management plus secondary actions).

The location and timing where secondary actions are needed cannot be anticipated in all cases. Thus, inclusion of secondary actions is one way of adapting management as restoration progresses. For example, a given tide-gate option may perform well on most objectives but fall short in marsh surface drainage. This would indicate very specific secondary actions to bolster marsh surface drainage in areas where it is needed and would be most effective.

Secondary actions may range from simple independent decisions to complex decisions that are conditionally linked to other management actions. The timing of some secondary actions may have a temporal relation with the tide-gate operations, thus requiring coordination with the tide-gate management process. For example, removal of vegetation may be beneficial to occur prior to restoration of extensive tidal exchange to facilitate work in more conducive, drier conditions.

Prediction of Option Consequences

Decision making is future oriented; good decisions are made after full consideration of What is likely to happen if this or that is done? Therefore, predicting the consequences of management actions is an important step in decision analysis. Expected performance, in the terms of each objective, is predicted under each option. A comparison of the relative predicted performance among alternatives provides the basis for selecting an option or, in the case of a multiple-objective problem, the information needed for conducting a tradeoff analysis. For Herring River restoration, the conceptual linkages between tide-gate and secondary management actions and restoration objectives are diagrammed in appendix 1.

Methods for prediction are based on either quantitative models or expert judgement. The methods for prediction are being developed in a tiered approach and are identified in table 1. The first tier (Tier 1) predictions are best professional judgments developed by the HRRC. The second tier (Tier 2) predictions are those provided through formal elicitation methods by subject matter experts and, where appropriate, community stakeholders. The third tier (Tier 3) predictions

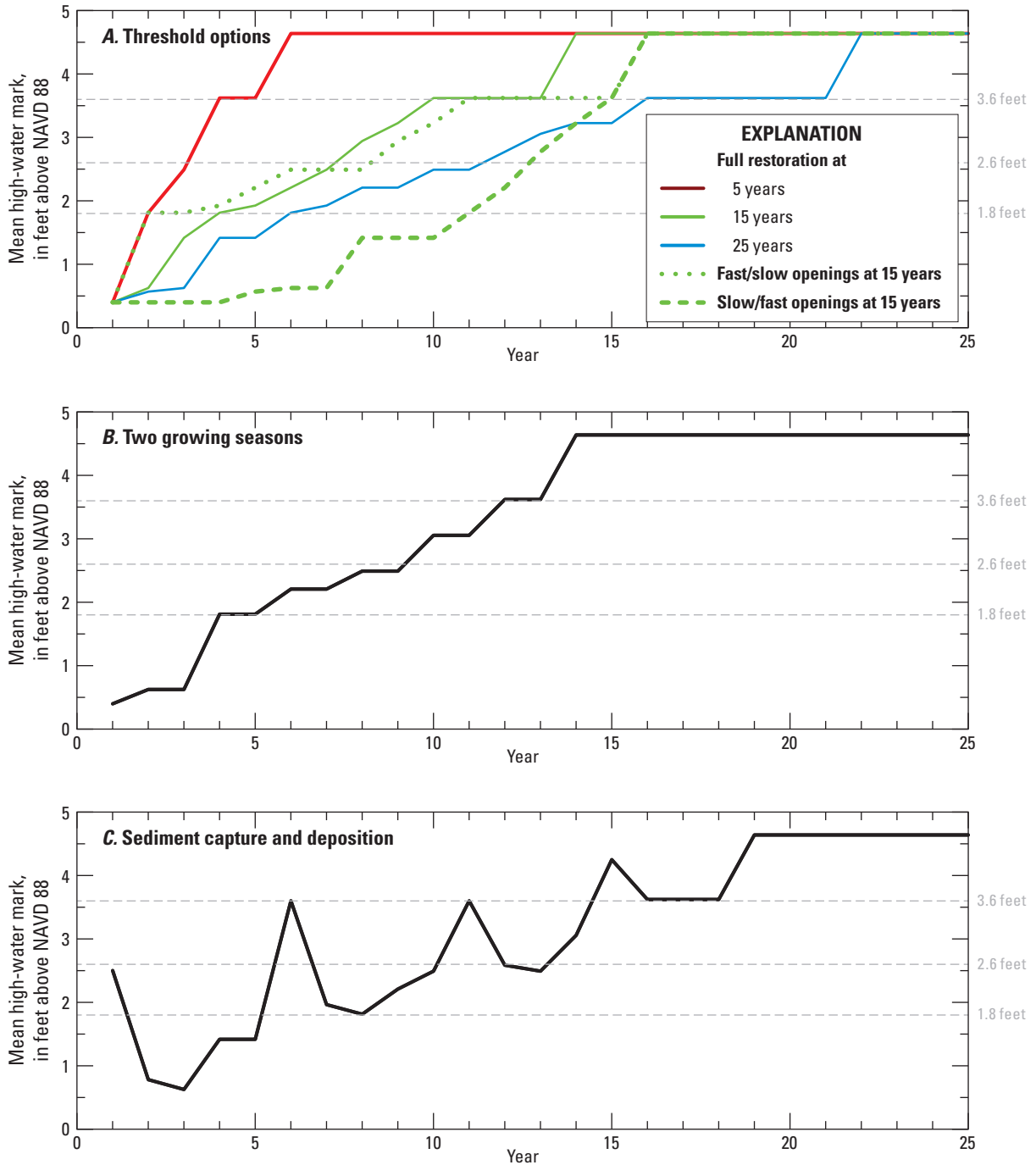


Figure 3. Effects of alternative gate operations on mean high water (MHW) for the Herring River estuary, Massachusetts: *A*, Threshold options to achieve full restoration (4.5-foot MHW) at 5, 15, or 25 years (yr); deviations in the time to reach 4.5-foot MHW are due to constraints on gate openings. Variations of the 15-year option include initially slow then fast opening (Slow.Fast 15-year option) and initially fast and then slow opening (Fast.Slow 15-year option). *B*, An option that pauses openings for 2 growing seasons to allow for aquatic vegetation to become established. *C*, An option with timing of openings to allow for upstream sediment capture and deposition. Horizontal lines show reference water levels.

are generated by quantitative models. Typically, accuracy and cost increase from Tier 1 to Tier 3; however, the value of the information to the selection of the tide-gate option does not necessarily indicate that Tier 3 predictions are warranted for all objectives. For predicting the percent coverage of non-invasive emergent vegetation, expert elicitation using available expertise from the HRRC is the Tier 1 method, and expert elicitation using a panel of experts is the Tier 2 method. In contrast, the model-based Environmental Fluid Dynamics Code (EFDC; <https://www.epa.gov/ceam/environmental-fluid-dynamics-code-efdc>; Hamrick, 1996), which predicts hydrology and water-quality dynamics for surface water, coupled with the Sea Level Affecting Marshes Model (SLAMM; <http://warrenpinnacle.com/prof/SLAMM/index.html>; Warren Pinnacle Consulting, Inc., 2012), is considered the Tier 3 method for predicting the percent coverage of non-invasive emergent vegetation. Tier 1 predictions have been compiled but are being used only to assess and develop the decision framework. Tier 2 and 3 predictions will be used for the decision analysis. Tier 3 predictions can be applied only when a cost-effective quantitative model exists for a given objective. Where no quantitative model is available, Tier 2 predictions will be elicited from technical subject-matter experts and community stakeholders through formal elicitation processes.

Planning for expert elicitation is currently underway (2019) to develop predictions for objectives where use of a quantitative model is not possible or otherwise suitable. Elicitation is a formal process where technical subject-matter experts or stakeholders are asked to provide their own informed judgments about how a specific management action, integrated within a platform option, may affect a specific objective (McBride and Burgman, 2012; O'Hagan, 2019). There are various methods for conducting formal elicitations, but the basis of the process is to develop data that allow for quantification of uncertainty and express the range of predictions among multiple experts or responders. For the Herring River, two separate elicitation processes are currently (2019) being planned: one for scientific experts to provide predictions for several measurable attributes for ecological objectives and another for local stakeholders to develop information about socioeconomic outcomes that are not addressed by existing ecological models. We predominately used the four-step question format combined with a modified Delphi format to capture uncertainty (Speirs-Bridge and others, 2010).

The foundational quantitative model for the Herring River project is a two-dimensional hydrodynamic model developed by the Woods Hole Group (2012) using the EFDC software package (Hamrick, 1996). The EFDC model spatially represents the entirety of the historical Herring River flood plain and has been calibrated and validated to a set of tidal observations collected over full lunar cycles in 2007 and 2010. The model has been used to identify the optimal size of the tide gates at the new CNR bridge, the location of the proposed Mill Creek dike, and the road culverts to be replaced as part of the restoration project. It has also been used to simulate the extent of tidal exchange under a range of full and partial resto-

ration scenarios. Outputs from the EFDC model include tidal metrics under normal and storm-driven tidal forcing, including water-surface elevations, tidal range, water-column salinity, flow direction and velocity, and hydroperiod (for example, residence time, flood frequency, flood duration). Data outputs are available for virtually any Herring River location within the model domain and for any time step within the lunar tidal cycle.

The EFDC model has been run to simulate 17 different tide-gate configurations at the CNR bridge to understand the hydrodynamic effects of incremental tide-gate management. Output from these simulations provides predictions of low- and high-tide water-surface elevations and other hydrodynamic metrics, averaged by subbasin and for individual and grouped model nodes. In addition to tabular data output, spatial data have also been compiled to graphically depict the extent of tidal exchange under each of the 17 tide-gate configurations.

In addition to the EFDC hydrodynamic model, other computer-based models have been applied to the Herring River project. The Sea Level Affecting Marshes Model (SLAMM) is open-source software that was originally developed with U.S. Environmental Protection Agency funding in the 1980s (Warren Pinnacle Consulting, Inc., 2016). It incorporates several input parameters, including Light Detection and Ranging (lidar) survey elevations, existing wetland classifications, sea-level-rise rates, tidal range, and accretion and erosion rates for various wetland habitat types to simulate the dominant processes involved with wetland conversions resulting from sea-level rise (Woods Hole Group, 2018).

Although typically utilized to project wetland changes owing to sea-level rise, SLAMM was applied in a unique approach to advance the understanding of how the changing tidal regimes associated with various tide-gate scenarios could potentially affect ecological resources and wetland types throughout the Herring River system. Used in combination, land elevation and tidal range are the main drivers of the simulated vegetation predictions. Rather than using SLAMM to predict water-level increases that are projected to occur because of sea-level rise, this application of SLAMM used different tidal ranges resulting from various tide-gate configurations at the CNR Dike to project how the vegetation would likely respond to changes in tidal conditions.

Other quantitative models either have been developed or are being considered for use for predicting outcomes. The U.S. Geological Survey developed a reactive-solute transport model of sediment release of nutrients in response to tidal flooding based on the Nutrient Flux Model (PHAST; Parkhurst and others, 2010). A fully functional version of this water-quality model is not currently available, but in the future, such a model could be used to simulate water chemistry change as salt marshes are restored. The Marsh Equilibrium Model (Morris and others, 2002) is being evaluated for its potential use in simulating sediment and marsh accretion processes and its ability to be integrated with output from the EFDC hydrodynamic model. Other analytical models are being investigat-

ed to generate quantitative predictions for other water-quality variables, sediment deposition, habitat suitability, and vegetation composition.

Evaluation of Tradeoffs

Predicting consequences provides information on the expected performance of individual objectives in response to available management actions. An analysis of tradeoffs among objectives then provides insight into the decision problem and helps decision makers and stakeholders deliberate about the alternative strategies by considering all objectives and their possible interactions. A consequence table is a useful tool for integrating the components of a decision analysis (that is, objectives, alternatives, and consequences) when conducting a tradeoff analysis (table 2). The predicted performance for each objective under each option is presented concisely in the unweighted consequence table. Relative weights are assigned to each objective on the basis of their importance, which can vary among stakeholders. Comparison of options is based on the overall value-weighted performance considering all objectives (Goodwin and Wright, 2014). Software applications have been developed within the R programming environment (R Core Team, 2018) for use by the HRRC to conduct tradeoff analyses for the Herring River restoration.

There are seven steps in the tradeoff analysis.

1. Populate the consequence table with predicted outcomes for each objective under each alternative action or option.
2. Develop utility curves (described below) for each objective reflecting how the range of possible outcomes are valued by stakeholders. Values may not be linear relative to outcomes, and utility curves can capture risk attitudes.
3. Use the utility curve to determine the utility value associated with each predicted outcome.
4. Replace the predicted outcomes with the associated utilities in the consequence table.
5. Assign an importance weight to each objective.
6. Calculate a weighted average of the utility values across the objectives for each alternative action.
7. Evaluate the sensitivity of the tradeoff analysis to uncertainty and identify options that are robust to uncertainty.

Utility functions transform performance metrics into a standardized scale (between 0 and 1) to represent preference for levels of performance and tolerance for levels of risk (fig. 4). Utility curves take a variety of shapes depending on risk attitude ranging from risk aversion to risk seeking. Risk attitude relates to one's tolerance for accepting the chance of a bad outcome for the possibility of better performance. A risk-seeking attitude arises when someone is unsatisfied with the prospect of low performance for an objective and is willing

to take chances to achieve a better outcome. A risk-averse attitude applies to someone who is unwilling to trade existing performance for the unlikely event of better performance when there is also some risk of doing worse than expected. It is common that choices involving gains (for example, improved ecological function) are risk averse; whereas, choices involving losses (for example, avoid adverse effects) are risk seeking (Tversky and Kahneman, 1986). To understand the possible range of stakeholder risk attitudes related to the restoration of the Herring River estuary, utility curves were elicited from the members of the HRRC for a subset of objectives expected to cover this range (appendix 2). Default utility curves were created for each objective based on the elicitation, but the utility curves can be adjusted within the R application prior to conducting a tradeoff analysis.

Implementation of an Option Through Time

Opening of the tide gates at the CNR dike will occur over a definite period of less than 25 years. Gate operation from closed to fully opened has been envisioned as alternative actions composed of incremental tide-gate openings. The HREC will select the tide-gate option with secondary actions based on recommendations from the HRRC informed by the tradeoff and risk analyses. The selected tide-gate option will be implemented followed by monitoring of outcomes. The selected tide-gate option will stipulate a schedule for gate operation over a 25-year period or until the gates are fully open, whichever occurs first. However, there are two ways the selected option can be adapted over time. First, the selected option can be reviewed periodically by repeating tradeoff analyses using updated or new information. The new information based on monitoring data would be used to update predictions based on revised estimates of model parameters in EFDC or SLAMM. Monitoring locations (table 1) are based on protocols developed under the Cape Cod Ecosystem Monitoring program, such as the hydrology protocol developed by McCobb and Weiskel (2003), and rely on general guidance provided by Buchsbaum and Wigand (2012) (see also <https://www.nps.gov/caco/learn/nature/cape-cod-monitoring-program.htm>). The tradeoff analysis would be conducted with new baseline determined by the current gate openings and hydrology. If indicated, a new option could be selected if the updated tradeoff analysis indicates that another option is likely to outperform the current option. For the initial 3–5 years, reviews would be conducted annually to evaluate short-term responses triggered by increases in water-surface elevation; the period between reviews can then increase as needed until full restoration is achieved. Second, monitoring can indicate the need to change secondary management actions. The thresholds that indicate secondary management action have not been stipulated. However, deriving thresholds need not be complex because the need for action could be evident. For example, monitoring can locate where drainage is insufficient to prevent ponded water at low tide, and in response, channel modifications can be used to increase local drainage.

Table 2. The unweighted consequence table for the pilot tradeoff analysis. The predictions are the modeled and most likely (expected) elicited values. The predicted values were transformed onto a utility scale accumulated over a 25-year period of restoration. The maximum performance on any given objective is indicated by a score of 25 because year-specific scores are summed over the 25-year period and maximum performance in any given year is 1.—Continued

[Subobjectives marked with a single asterisk (*) report the average cumulative utility for the nine subbasins. Subobjectives marked with a double asterisk (**) report the average cumulative utility for the variable areas in each measurement target range. All other subobjectives report the basin-wide cumulative utility. T, threshold option for for 5 (_5), 15 (_15), or 25 (_25) years; FS, fast.slow 15-year option; SF, slow.fast 15-year option; MHW, mean high water; MLW, mean low water; DO, dissolved oxygen; WQ, water quality; Veg, vegetation; rec, recreation; TE, threatened & endangered species; Sed, sediment; GS, growing season]

Objective hierarchy			Tide-gate option (figure 3)						
Fundamental objective	Objective	Subobjective	T_5	T_15	FS_15	T_25	SF_15	GS	Sed
Ecosystem services	Climate change mitigation	Climate	23.17	22.04	23.00	20.73	18.44	20.88	20.73
	Recreation	Existing rec	2.81	2.81	2.81	2.81	2.81	2.81	2.56
		Golf	20.76	20.76	20.76	20.76	20.76	20.76	20.76
		New rec	21.94	13.93	16.00	11.31	13.73	14.87	14.87
	Shell fishing opportunities	Shellfish acres	18.72	18.69	18.83	18.19	18.17	18.87	18.19
		Shellfish closure	21.44	21.42	18.92	21.41	21.40	21.41	21.41
	Natural mosquito control	Mosquitos							
Cost	Cost of tide-gate operations	Gate hours	17.57	18.18	18.80	18.18	18.18	15.97	11.92
	Cost of monitoring	Monitoring hours	13.81	12.12	14.10	11.27	12.12	12.12	12.12
	Cost of secondary actions	Secondary cost	23.93	23.93	23.93	23.93	23.93	23.93	23.93
Threatened and endangered species	Monitoring	T&E	19.91	19.91	20.60	19.91	19.91	16.09	14.63

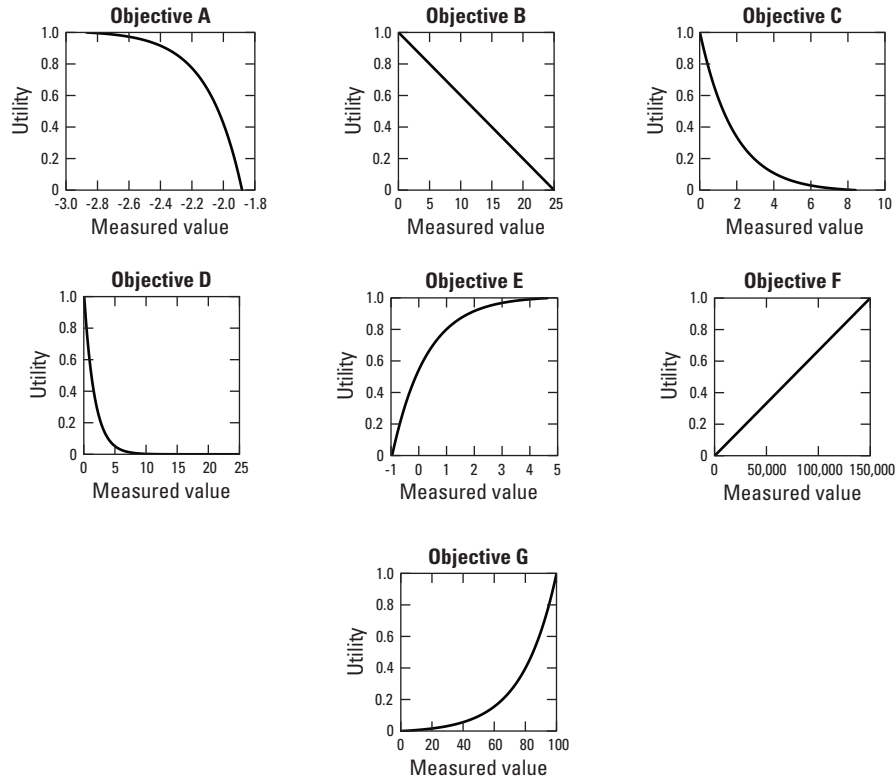


Figure 4. Example utility curves for selected objectives relating the level of a performance metric for hypothetical objectives (x-axes) to a standardized score between 0 and 1 (y-axes) based on preferences and risk attitude. The utility curves are for minimized objectives (A–D), maximized objectives (E–G), risk-averse attitudes (A and E), risk-seeking attitudes (C, D, and G), and risk-neutral attitudes (B and F).

Prototype Decision Analysis and Results

A decision analysis was conducted using preliminary predictions to serve as a starting point, evaluate the decision structure, and identify areas needing improvement. The seven steps outlined in the “Evaluation of Tradeoffs” section were conducted using predictions from the EFDC model for hydrological objectives, the SLAMM model for certain ecological objectives, and preliminary expert-elicited predictions for the remaining objectives. Members of the HRRC participated in the prototype analysis by providing expert judgment on many of the performance measures. To limit the potential for elicitation fatigue, the initial prototype focused on the lower Herring River subbasin for hydrologic and ecological objectives and basinwide for socioeconomic objectives. It was assumed that the Mill Creek and Upper Pole Dike Creek water-control structures were in place to limit the scope of the elicitation. The uncertainty comes from the elicited attributes. The numerical models do not yet produce confidence intervals, which will be included in future prototypes.

The tradeoff analysis was conducted using a custom software application developed in the R programming environment (R Core Team, 2018). The application allowed for selection or specification of utility curves, prediction percentile, and importance weighting of the objectives. The prediction percentile, which ranged from 0.55 to 0.8, was used to compute confidence limits. For each percentile, the corresponding confidence limits represented worst case (pessimistic) and best case (optimistic) contingent on whether the objective was to be minimized or maximized. Utility curves ranged from risk averse to risk seeking options on a continuous scale and were used to transform the performance measures to utility values between 0 and 1. Some utilities were time specific. For example, the utility curve could be differentiated for different phases of restoration (for example, specifying risk aversion during early restoration and risk neutral or risk seeking late in the restoration planning cycle). A discount rate can be set to place higher value on performance during the first few years relative to performance near full-gate opening.

The scores in the consequence table, which are cumulative utilities over the 25-year restoration period, range from 0 to 25 corresponding to performance from poor to excellent

for a given objective and tide-gate option (table 2). Thus, the consequence table can be scanned quickly to see how well the objectives are being met by comparing the scores to the maximum value of 25 and to the minimum value of 0.

The overall score for an option is a weighted average of the cumulative utilities across all objectives (table 3). The objective weights in table 3 were allocated as follows: the hydrologic objectives received 30 percent, ecological function objectives received 20 percent, adverse effect objectives received 30 percent, ecosystem service objectives received 10 percent, cost objectives received 5 percent, and threatened and endangered species received 5 percent, which is the balanced-weighting scenario presented in figure 5. The overall score is also scaled from 0 to 25, indicating poor to excellent performance of a given option. The overall scores, along with the more detailed objective-specific comparisons, provide a tool for comparing options and exploring the predicted outcomes of different options to gain a better understanding of the problem and potential management consequences.

Option scores and rankings change depending on choice of utility and importance weighting, as well as the level of confidence in the prediction. Thus, to complete the tradeoff analysis, it is important to determine whether the best-performing option is sensitive to variation in stakeholder values or prediction uncertainty as represented by different levels of pessimistic and optimistic scenarios; we refer to this as a sensitivity analysis. The goal is to identify options that are robust to variation in stakeholder values and prediction uncertainty. In other words, the goal is to find an option that is predicted to perform well across a wide range of underlying assumptions.

A sensitivity analysis was conducted in which the tradeoff analysis was repeated assuming different levels of prediction uncertainty and value-weighting schemes. To test the effect of uncertainty, the tradeoff analysis was conducted using the most likely prediction and again using the limits from the confidence interval with a range of percentiles (0.55–0.80). The confidence limit to be used depends on whether a best case or worst-case scenario is being evaluated and the objective’s direction. If an objective is to be maximized, then the upper confidence limit is considered the best-case outcome. In contrast, if an objective is to be minimized, then the lower

confidence limit is the best case. Four weighting schemes were included in the sensitivity analysis, and these included either (1) a preference for ecological objectives, (2) a preference for socioeconomic objectives, (3) a balance between ecological and socioeconomic objectives, or (4) an equal weighting of each fundamental objective (fig. 5). In an ecological weighting scheme, hydrography and ecological objectives are highly valued. In a socioeconomic weighting scheme, the social and economic objectives are highly valued. In a balanced weighting scheme, some ecological (hydrography) and some social (adverse effects) objectives are highly valued. In the equal weighting scheme, all fundamental objectives are equally valued. Aspects of the analysis that can be investigated include average performance (fig. 6) and frequency of ranking (fig. 7). For example, based on the preliminary predictions, the “15-year Fast.Slow” option (fig. 3A) was ranked first more frequently than other options (fig. 7). The predicted performance of this option was quite robust to underlying assumptions about uncertainty and value weighting because it was ranked first more frequently than other options and was never ranked below second (fig. 7). The only other option that ranked first was the 25-year option (fig. 3A), which was rarely ranked below 3rd and never below 4th (figs. 6 and 7).

Although it is important to identify which option has the best and most robust overall performance, it is also important to evaluate how well individual objectives and subobjectives are being met. A double-column chart shows option performance at the objective level (fig. 8). There are two questions that a double-column chart is designed to answer. First, does performance among option alternatives vary, or do all options perform similarly? Second, is there unmet potential for better performance, or does the best performing option achieve full or nearly full performance? For example, for the Ponding objective there is a wide range in performance among option alternatives, but there is only modest room for improvement because the option that performs best for this objective nearly achieves maximum performance (fig. 8). In contrast, for the Deposition objective there is a narrow range in performance with all options performing about the same, and there is ample room for improvement (fig. 8). Maximizing sediment deposition and accretion, minimizing damage to structures, and

Table 3. Overall utility from the pilot tradeoff analysis. The cumulative utilities for each objective, which are presented in table 2, are value weighted and averaged for an overall performance score for each option. The objective weights in table 3 were allocated as follows: the hydrologic objectives received 30 percent, ecological function objectives received 20 percent, adverse effect objectives received 30 percent, ecosystem service objectives received 10 percent, cost objectives received 5 percent, and threatened and endangered species received 5 percent, which is the balanced-weighting scenario presented in figure 5.

Option score	Options (figure 3)						
	Threshold 5 year	Threshold 15 year	Threshold 25 year	Fast.Slow 15 year	Slow.Fast 15 year	Growing season	Sediment
Weighted sum	14.99	15.19	15.67	15.79	14.92	14.92	15.42
Rank	5	4	2	1	6	7	3

maximizing existing recreation are objectives with potential for additional performance. Performance at the individual objective level or overall option level is affected by the assumed utility curves. For example, the utility for incurred damage (fig. 4D) drops off precipitously for incidences greater than 0; thus, there is very little tolerance for any occurrence of damages. There is high confidence that damage incidences will be low (less than or equal to 2 for the life of the project); however, the extreme utility (fig. 4D) penalizes performance even for a few such incidences. The 15-year Fast.Slow (P_15_FS) option earns the highest cumulative utility after 25 years in all

four value weight scenarios and at all levels of uncertainty, but the rank of the other options, and the difference between the P_15_FS option and the other options, vary across weighting scenarios (fig. 9). For each level of uncertainty in fig. 9, the corresponding confidence limits represented worst-case and best-case values contingent on whether the objective was to be minimized or maximized. Varying the levels of uncertainty and the interval between worst- and best-case outcomes had small effect on the range of 25-year cumulative utilities compared to different value weighting scenarios.

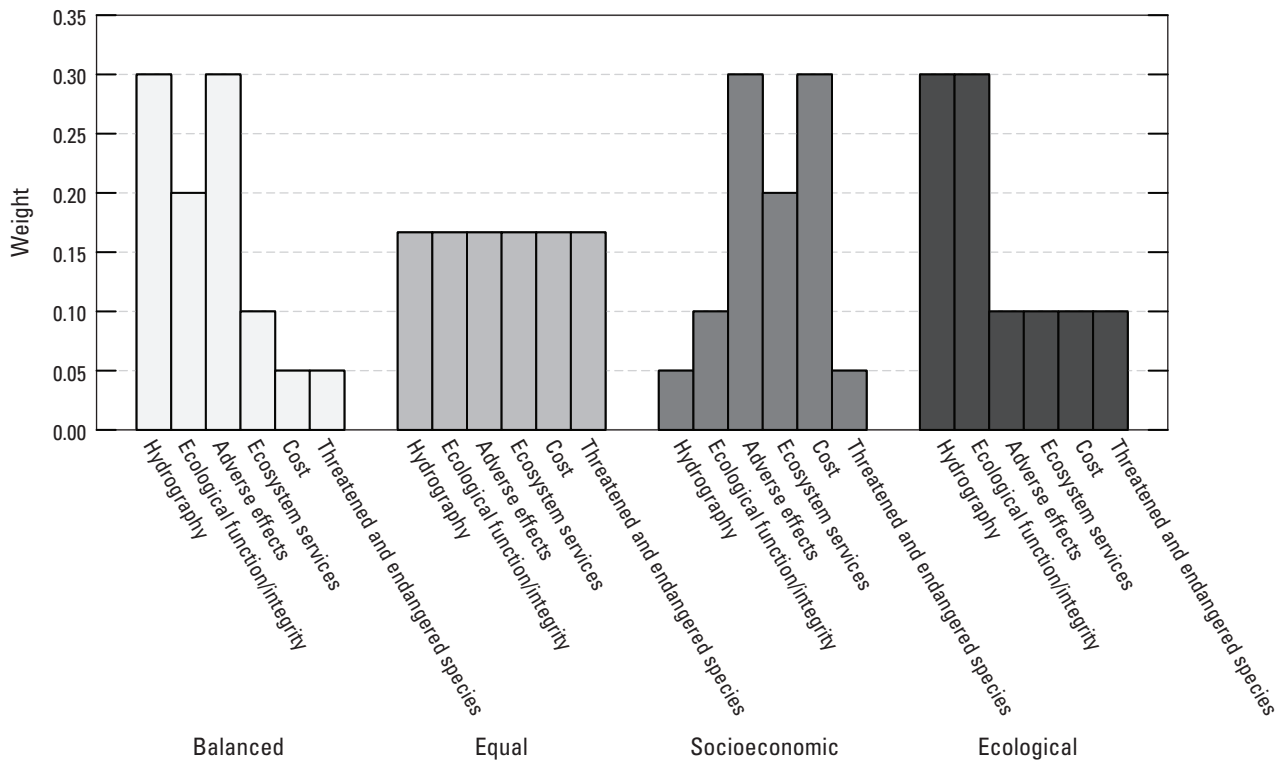


Figure 5. The four weighting schemes applied to the fundamental objectives to evaluate outcomes. In a balanced scheme some ecological (hydrography) and some social (adverse effects) objectives are highly valued. In the equal scheme, all fundamental objectives are equally valued. In a socioeconomic scheme, the social and economic objectives are highly valued. In an ecological scheme, hydrography and ecological objectives are highly valued.

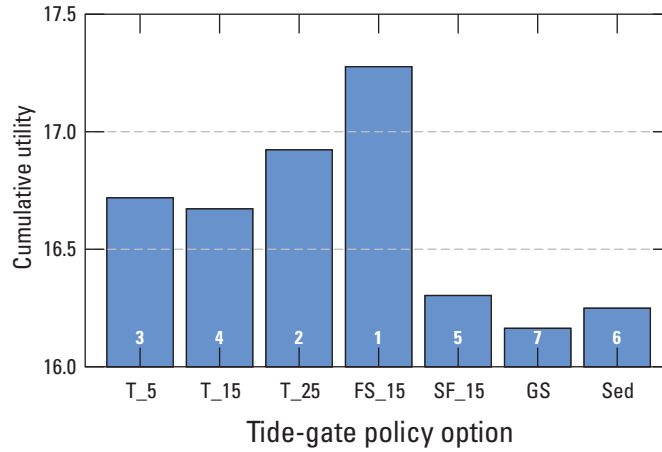


Figure 6. Cumulative utility averaged across a range in prediction uncertainty and the four value-weighting schemes in figure 5 to compare seven tide-gate options in figure 3. The numbers inside each bar indicate the rank of each option. The average cumulative utility for all seven options after 25 years were within 1.5 utility points of one another. (T, threshold option for 5 (_5), 15 (_15), or 25 (_25) years; FS, fast.slow 15-year option; SF, slow.fast 15-year option; GS, growing season; Sed, sediment)

	Policy option						
	T_5	T_15	T_25	FS_15	SF_15	GS	Sed
Rank (Lower is better)	0	0	0.12	0.88	0	0	0
2	0.33	0	0.56	0.12	0	0	0
3	0.19	0.31	0.25	0	0	0	0.25
4	0.23	0.67	0.08	0	0.02	0	0
5	0.19	0.02	0	0	0.48	0.06	0.25
6	0	0	0	0	0.19	0.81	0
7	0.06	0	0	0	0.31	0.13	0.5

Figure 7. Frequencies of ranks based on cumulative utility after 25 years for seven options (figure 3) across a range in prediction uncertainty and the four value-weighting schemes in figure 5. Frequencies greater than 0 up to the maximum are increasingly darker blue. (T, threshold option for 5 (_5), 15 (_15), or 25 (_25) years; FS, Fast.Slow 15-year option; SF, Slow.Fast 15-year option; GS, growing season; Sed, sediment)

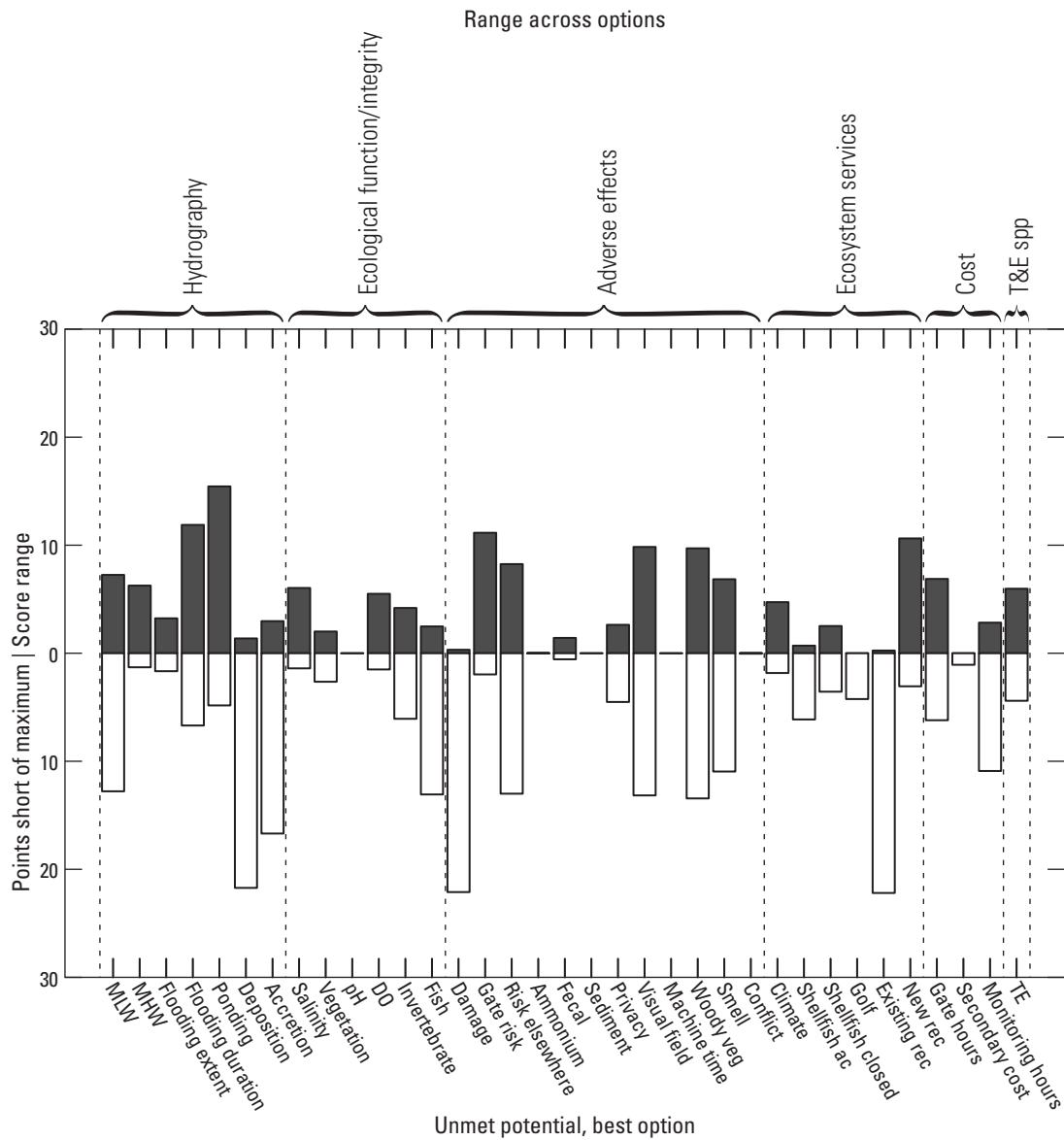


Figure 8. Double-column chart used to evaluate how effectively the tide-gate options address all objectives. The upper (dark) columns report the spread in cumulative utility after 25 years between the highest and lowest ranking option for each objective. A taller column indicates a greater range among options, whereas a shorter column indicates all options were more similar. The lower (light) columns report how much utility was unrecovered by the best option. A shorter column indicates the objective was well addressed by the best option, and a taller column indicates even the best option did not completely address the objective. (MLW, mean low water; MHW, mean high water; DO, dissolved oxygen; Veg, vegetation; ac, acres; TE, T&E Spp, threatened and endangered species; rec, recreation)

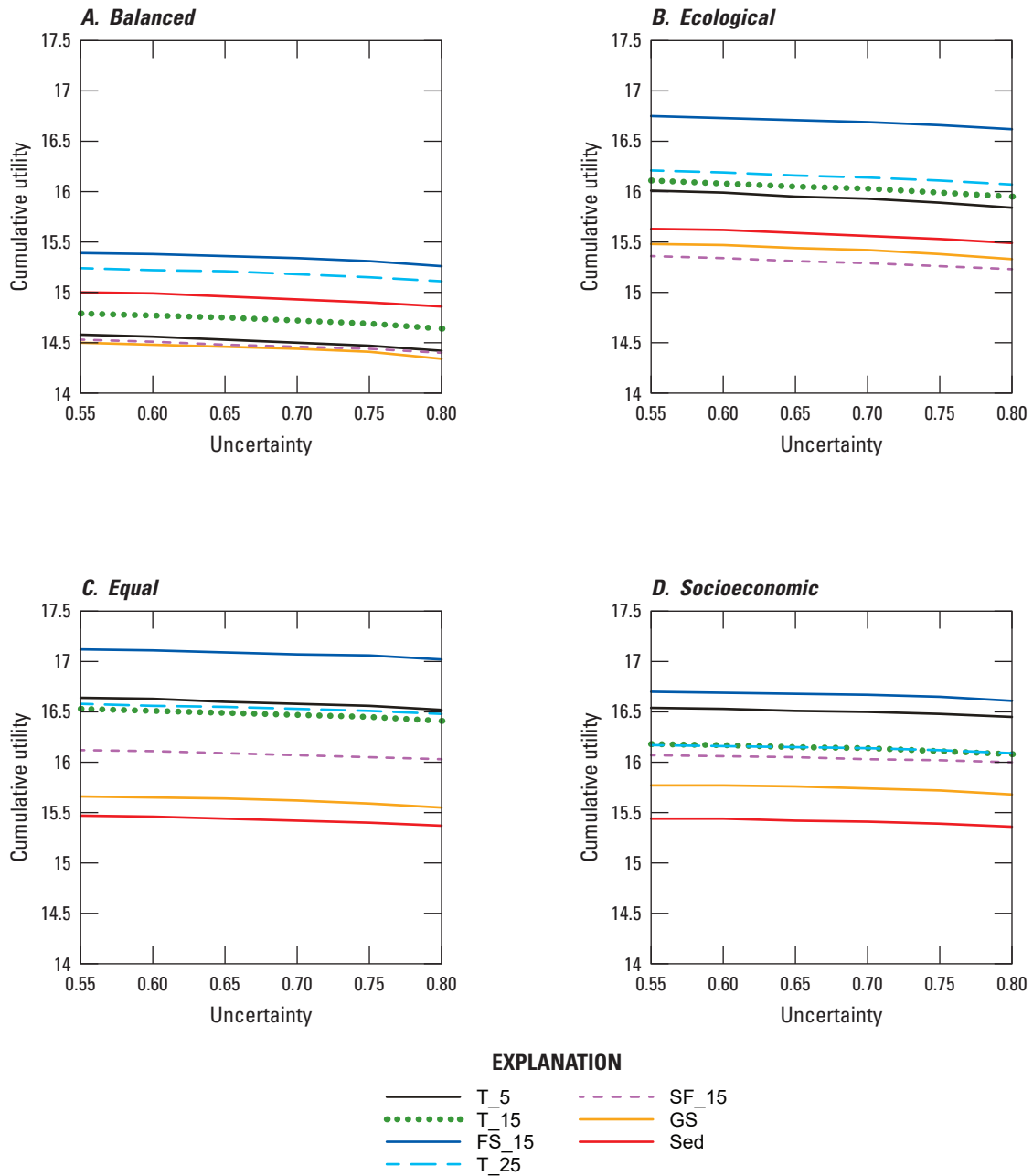


Figure 9. Cumulative utility as a function of uncertainty formulated as the percentile for which confidence limits were computed for value weights: *A*, balanced, *B*, ecological, *C*, equal, and *D*, socioeconomic. For each level of uncertainty, the corresponding confidence limits represented worst-case and best-case values contingent on whether the objective was to be minimized or maximized. Varying the levels of uncertainty and the interval between worst- and best-case outcomes (x-axes) had a small effect on the range of 25-year cumulative utilities compared to different value weighting scenarios (panels). (T, threshold option for 5 (_5), 15 (_15), or 25 (_25) years; FS_15, fast.slow 15-year option; SF_15, slow.fast 15-year option; GS, growing season; Sed, sediment)

Next Steps

The decision structure developed for the Herring River restoration is complex due to the multiple-stakeholder concerns and the importance of the estuary from hydrological, ecological, and socioeconomic perspectives. The tide-gate options are structured around restoring the tidal range, which is the ecological basis for restoration. Predicting outcomes is a continuing challenge because of the many and varied objectives. The decision structure represents a good-faith effort to include all stakeholder concerns and provide decision makers with a transparent approach to incorporate those concerns in comparisons of tide-gate options using the best-available science.

Eventually, the decision structure can be simplified by removing objectives that are insensitive to decision choice or eliminating dominated alternatives from further consideration. However, at this point we do not want to simplify the problem for a couple reasons. First, there is a communication value in demonstrating that a comprehensive set of objectives is being considered, even though some objectives do not affect the decision choice. Second, the prediction methods are still being developed and improved; thus, the consequences are not finalized. It would be premature to simplify the problem, although eventually that is the aim.

Based on the prototype analyses, the 15-year Fast.Slow option (fig. 3) performed best among the policies analyzed. Secondary management actions could focus on addressing objectives not fully met, which can be identified using the double-column chart (fig. 8). Opportunities for improvement through secondary actions are related to sediment transport, damage, and existing recreation. The expected performance of the tide-gate option would need to account for updated information because the need for some secondary actions might not be foreseen.

The management process will be implemented over the project's finite time line (that is, less than 25 years before full gate opening). As restoration progresses, monitoring will be useful to identify additional areas where secondary actions are warranted. Also, periodic updating of predictive models and tradeoff analysis based on monitoring data can be used to determine whether adjustments in the selected option for tide-gate management are warranted as managers increase their understanding of system dynamics and the response to tide-gate manipulations.

Collaborative processes require, at a minimum, a clear problem statement, institutional support, an issue that warrants significant investment of organizational resources, interdependence among parties to achieve good outcomes, and a zone of possible agreement. For a collaborative process to achieve success, the parties need a shared vision and trust in the process. It is important that stakeholders and decision makers be explicit and transparent about what they care about, engage in creative development of tide-gate options, and use best-available science to forecast outcomes.

The next steps are to progress beyond the preliminary predictions and to move predictions from first cut (Tier 1) to

ideal method (Tier 3) wherever possible. Then the applications developed in R programming environment can be used to conduct the tradeoff and sensitivity analyses described and illustrated in this report to inform discussions within the technical and stakeholder committees and formulation of recommendations to the decision makers.

Summary

Ecological restoration typically involves a complex interaction of social, economic, and ecological considerations representing the mandate of resource stewards and the values of stakeholders. The success of ecological restoration can be determined by assessing whether tradeoffs among the multiple considerations and risks associated with uncertain outcomes are suitably evaluated and incorporated into decision making. Decision analysis was devised for evaluating tradeoffs and risks to inform management choices. In this report, the authors describe a decision analysis framework to evaluate the complex tradeoffs and risks associated with the restoration of the 1,100-acre Herring River estuary within Cape Cod National Seashore in Massachusetts. The tide gates at the Chequessett Neck Road (CNR) dike at the mouth of the Herring River have severely restricted tidal exchange for more than 100 years and caused ecological degradation to the estuary. The degradation of the basin and the structural integrity of the dike have motivated resource managers to pursue restoration of the Herring River estuary.

To develop the decision analysis framework, the authors worked with the Herring River Restoration Committee (HRRC) through a series of meetings with the full committee and a subgroup tasked with framework development. The HRRC represents the decision makers and stakeholders in the restoration process. Additional workshops with stakeholders, science experts, and regulators helped to elucidate underlying issues, incorporate concerns and interests into the framework, and resolve technical questions. The decision analysis for the Herring River restoration was structured according to six major components: (1) a clear statement of the problem, (2) comprehensive and measurable objectives, (3) a set of discrete tide-gate options, (4) a means to predict outcomes, (5) a process to evaluate the implications of these outcomes, and (6) a plan for implementation of the selected tide-gate option over time, including monitoring to provide feedback and to formally incorporate learning, reevaluate options, and possibly adapt management as restoration is implemented over time.

The decision framework is based on the understanding that representatives of Cape Cod National Seashore and the town of Wellfleet will be responsible for managing the new tide control gates at CNR, Mill Creek, and Pole Dike Creek and for implementing secondary management actions to achieve restoration goals. The goals are to restore the natural hydrography (that is, tidal range and marsh surface elevation) and ecological integrity of the Herring River estuary while minimizing adverse economic and social effects, maximizing

the estuary's production of ecosystem services, and minimizing management costs. Objectives that fit under the project goals define comprehensive performance measures useful for predicting and monitoring the consequences of management actions.

The primary management actions are to adjust the volume of tidal flow through a series of to-be-constructed tide gates at CNR, Mill Creek, and Pole Dike Creek; the tide-gate adjustments can vary by the number, location, magnitude of opening, and flow direction of the individual tide-gate openings at any given time. The sequence of tide-gate adjustments over the years of restoration form the basis for the management options. In addition, tide-gate options include secondary management actions, such as management of flood-plain vegetation or restoration of connectivity, intended to accelerate the recovery of the estuarine habitat, enhance the benefits of tidal restoration achieved through tide-gate management alone, and reduce the potential adverse ecological and socioeconomic effects of restoring tidal flow. Over a planning horizon, decisions involve the rate at which newly constructed water-control structures allow tidal exchange, and the timing and location of implementing numerous secondary management actions.

Performance, in the terms of each objective, is predicted for each tide-gate option using a range of methods from quantitative physical process models to elicited expert judgment. A comparison of the relative predicted performance among options provides the basis for deciding how to manage the tide gates. Decisions will affect biophysical (for example, sediment transport, discharge of fecal coliform bacteria) and ecological (for example, vegetation response, fish passage, effects on shellfish) processes, as well as socioeconomic interests (for example, effects on property, views, recreation). The framework provides a structured approach for evaluating trade-offs among multiple objectives (ecological and social) while appropriately characterizing relevant uncertainties and accounting for levels of risk tolerances and the values of decision makers and stakeholders.

In this project, an initial prototype decision analysis was conducted using a software application developed for evaluating tradeoffs and sensitivity of the decision to risk and uncertainty. The next near-term steps are to progress beyond the preliminary predictions, repeat the tradeoff and sensitivity analyses, and inform discussions within the technical and stakeholder committees who will formulate recommendations for the decision makers.

The management process is intended to be implemented over a finite time line (anticipated to be less than 25 years before full gate opening). As the restoration progresses, monitoring of outcomes can be used to identify additional areas where secondary actions are needed. Also, monitoring data can be used to update predictions and periodically repeat the tradeoff analysis to determine whether adjustments in the selected tide-gate management option are warranted as managers increase their understanding of system dynamics and the estuary's response to tide-gate manipulations.

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Appendix 1. Conceptual Models

The description and purpose of the conceptual models are presented in this appendix. Five figures (figs 1.1 to 1.5) are included, one for each of the fundamental objectives: hydrography, ecosystem function, ecosystem services, adverse effects, and cost. In each figure, the fundamental objective is on the right-hand side of the diagram in a green hexagon. Subobjectives that are nested under each fundamental objective are shown to the left of the hexagon in green rectangles, with arrows pointing from the nested subobjectives to the fundamental objective. There may be multiple layers of nested subobjectives, depending on the objective. These, too, will be in green rectangles and have arrows from them pointing into the upper-level objective. Moving to the left on the diagram, things that affect or have influence on the lowest level objectives are shown in purple rectangles. There are arrows from the purple rectangles to the lowest-level objective. Continuing to move from right to left, things that affect or have influence on purple rectangles are also shown in purple rectangles, with arrows pointing to the purple rectangle it influences. There

may be several influences depicted from right to left. Stochastic events or states are shown in red circles, again with an arrow pointing directly to the rectangle it affects. Decisions that are part of the decision-making process of the restoration are depicted in gray rectangles (that is, gate manipulations and secondary management actions). On the Minimize Adverse Effects diagram (fig. 1.3), black rectangles are shown. These are actions that can be taken but that are not part of the management aspect of the restoration. For example, the Structural Design of the dike will affect the safety of pedestrians, fishermen, and boaters; however, it is not part of the decision-making process of the restoration. Existing models that make predictions regarding the outcome of a given decision (gray rectangle) and a resulting state (purple or green rectangles) are shown in yellow diamonds. The yellow diamonds are placed on the arrow between two shapes: the shape to the left is the input to the model, whereas the shape to the right is the output of the model. Yellow diamonds (that is, predictive models) may also be placed between two state rectangles; that is, the input to the model does not have to start with a decision node. The influence diagrams serve many purposes. They

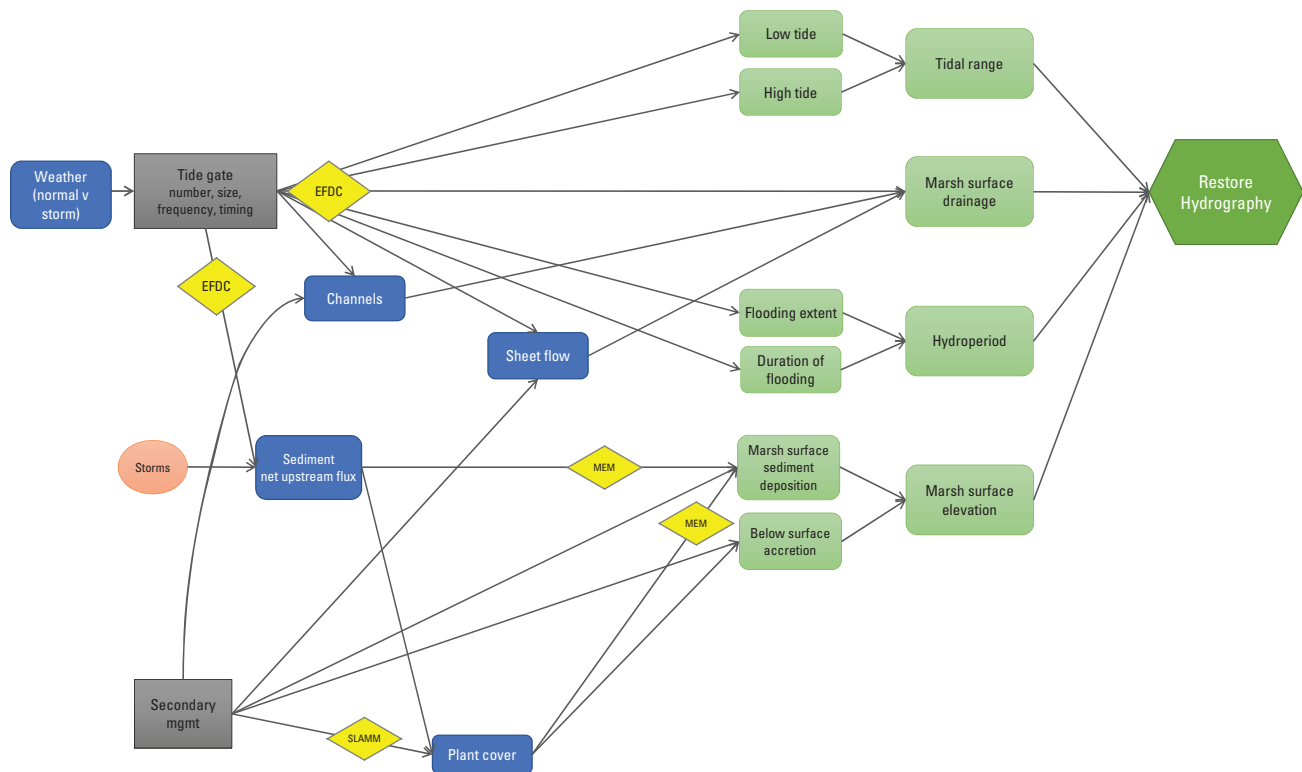


Figure 1.1. Conceptual model for the hydrography objective. (EFDC, Environmental Flow Dynamics Code; MEM, Marsh Equilibrium Model; SLAMM, Sea Level Affecting Marsh Migration; mgmt, management)

serve as depictions of conceptual models of how the system works regarding the objectives; the decisions we make and actions we take; and the effects that those actions have on the system, and ultimately, the objectives. The diagrams help to communicate our conceptual models. They help elucidate the areas where existing models predict outcomes of actions (for example, the Environmental Flow Dynamics Code [EFDC]) and where predictive models are absent and thus predictions

are based on expert elicitation. The diagrams will also help to identify alternative courses of action, or strategies, whose predicted outcomes can be compared with respect to the objectives. The influence diagrams include only as much detail as is necessary and useful for understanding the system and making predictions of outcome with respect to the objectives (that is, the green rectangles and green hexagon).

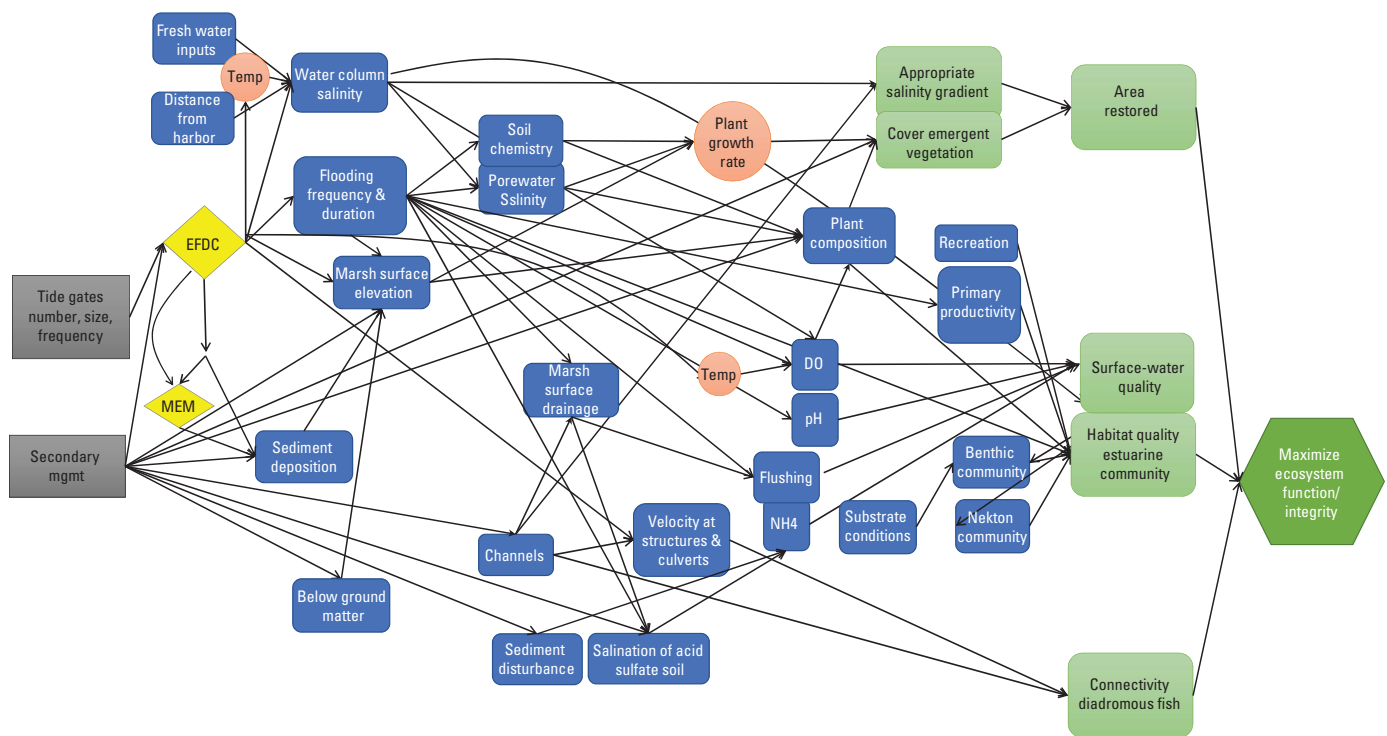


Figure 1.2. Conceptual model for the Ecosystem-Function objective. (EFDC, Environmental Flow Dynamics Code; MEM, Marsh Equilibrium Model; DO, dissolved oxygen; NH4, ammonium; mgmt, management; Temp, temperature)

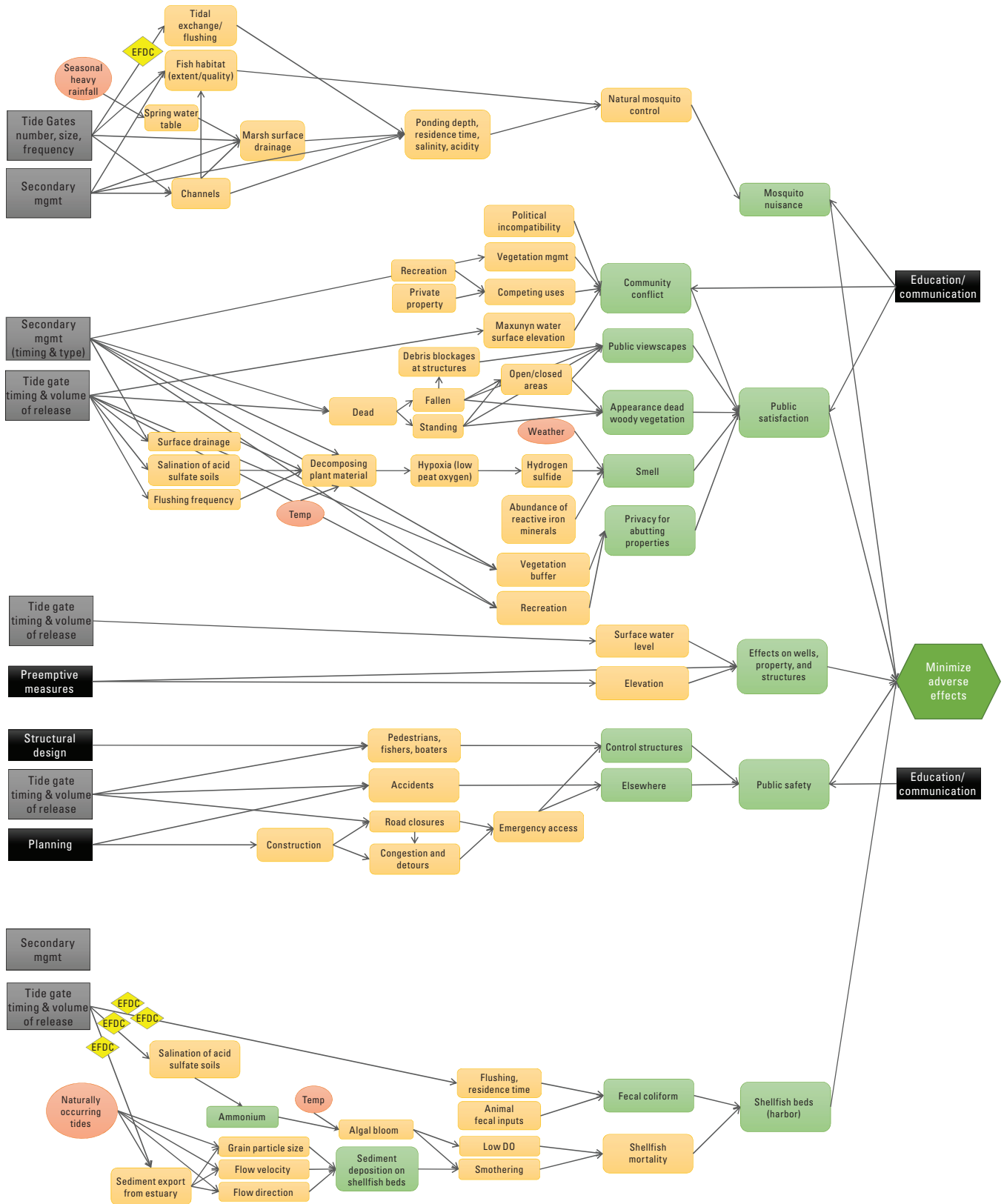


Figure 1.3. Conceptual model for the Minimize Adverse Effects objective. (EFDC, Environmental Flow Dynamics Code; Temp, temperature; DO, dissolved oxygen; mgmt, management; veg, vegetation)

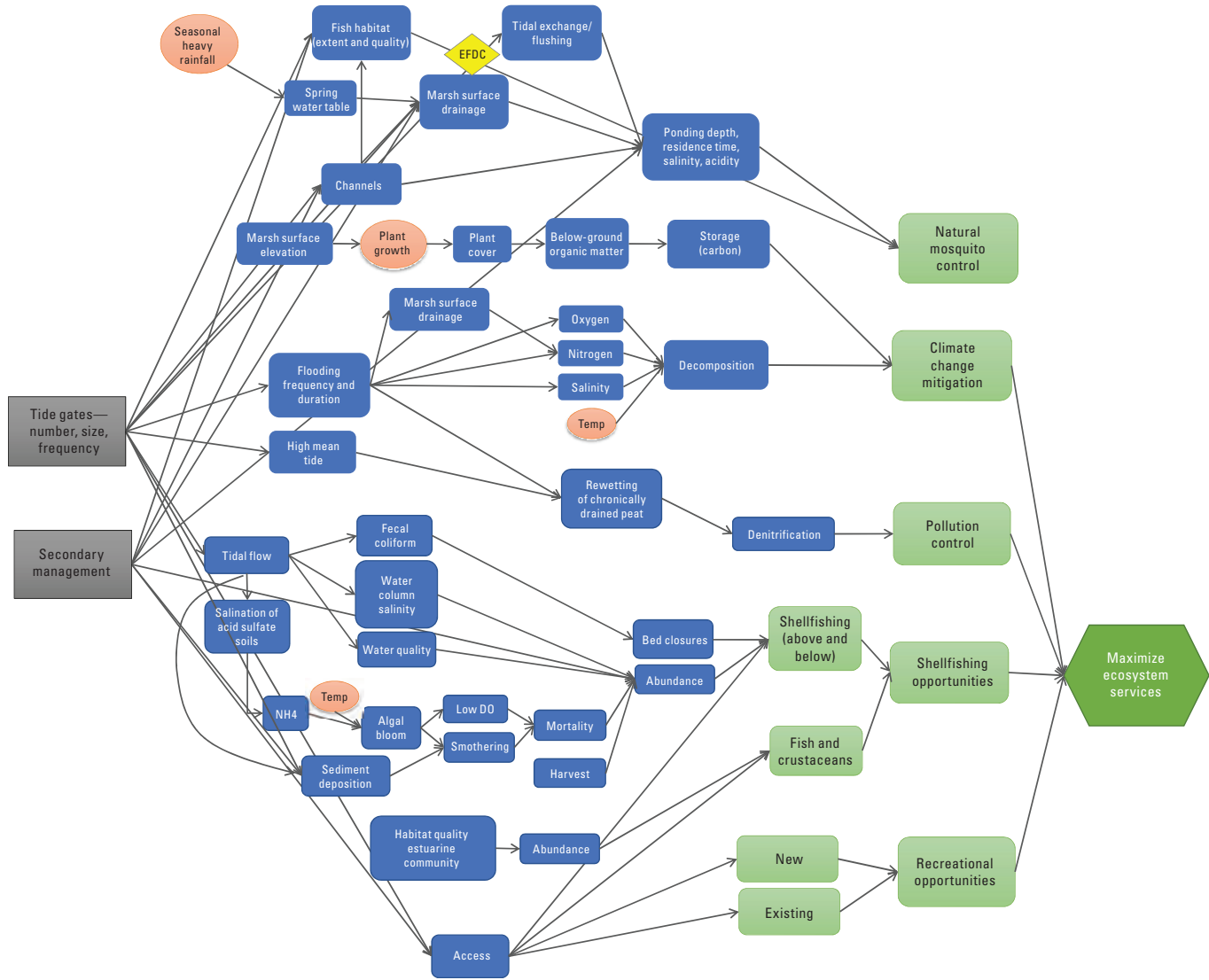


Figure 1.4. Conceptual model for Ecosystem-Services objective. (DO, dissolved oxygen; EFDC, Environmental Flow Dynamics Code; mgmt, management; NH4, ammonium; Temp, temperature)

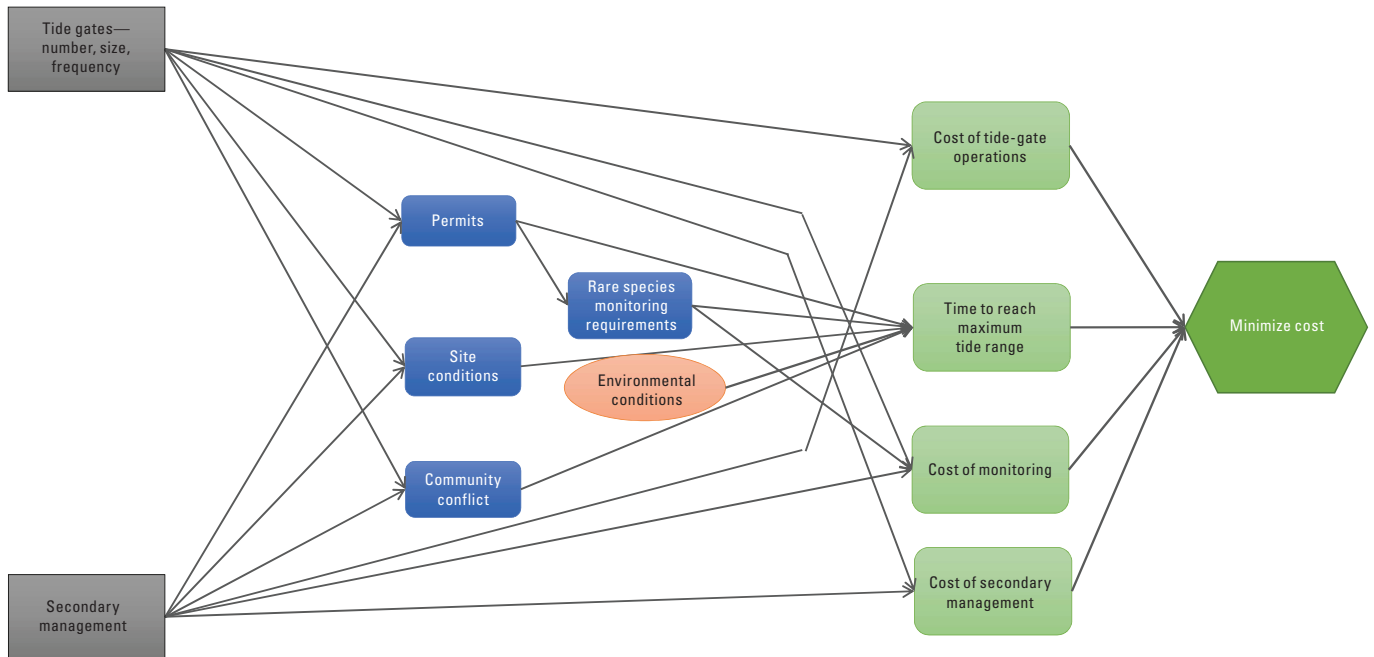


Figure 1.5. Conceptual model for Cost objective.

Appendix 2. Summary of Meeting with Herring River Restoration Committee to Elicit Utility Curves

In this appendix we, the facilitators, summarize results of an elicitation exercise conducted with the Herring River Restoration Committee (HRRC). The purpose of the exercise was to explore stakeholders' values and risk attitudes for a couple key objectives of the restoration project. Elicitation of values and risk attitudes is commonly used in decision science to help decision makers better understand the nature of tradeoffs and make a fully informed decision. This was chiefly a training exercise to verse the HRRC in this form of elicitation; the results we show below are not final.

The elicitation was conducted November 4–5, 2015, at the National Park Service headquarters during an HRRC monthly meeting. The methods are described, and the results are summarized chronologically.

Facilitators: Dave Smith, Jill Gannon, Mitch Eaton (U.S. Geological Survey)

Wednesday, November 4, 2015: Elicitation with the HRRC

Introduction and Practice

We introduced three different methods of elicitation: (1) setting up a gambling scenario (figs. 2.1 and 2.2), (2) bisection method, and (3) direct elicitation. All three methods, when followed, can result in a non-linear relation (that is, a curve), the shape of which describes the value a stakeholder assigns to each level of potential outcome, thus portraying how the person feels about risk (that is, risk averse, risk neutral, or risk seeking; fig. 2.3). We refer to this curve as a utility curve, where “utility” is the value or level of satisfaction a stakeholder feels regarding any potential outcome. All three methods have merit, and while theoretically each should produce the same relations, because of inherent idiosyncrasies of each method, they can result in different curves. We are seeking a method the committee understands and feels comfortable with. After reviewing the three different methods, the committee unanimously agreed that they preferred the first method—the gambling scenario. Given this agreement, we approached the elicitation exercise the following morning using only the first method.

In figure 2.1, you have a choice of either (1) being given \$100 without risk (“sure thing”) or (2) entering a gamble where you might win \$200 but risk getting nothing (\$0). The odds, or probability (p), of this gamble are unspecified. The question that needs answering is: What probability of winning the gamble and receiving \$200 (that is, the value of x) is needed for you to feel indifferent about the choice before you?

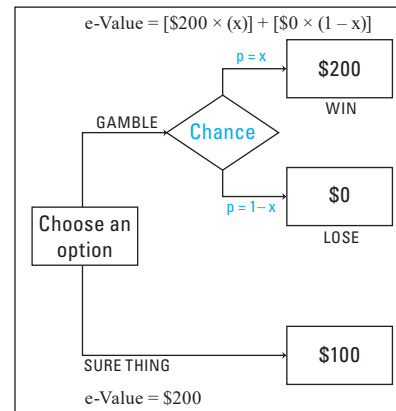


Figure 2.1. An introductory example of a gambling scenario.

For example, a value of $x = 0.5$ means that there is a 50-percent chance you will get \$200 and a 50-percent chance you will get \$0. Thus, the expected value (e-value) of that gamble, if repeated many times, would be \$100, which is equivalent to the expected pay off of choosing the “sure thing” as opposed to the gamble. A person who feels indifferent about the choice with a probability of 0.5 of winning the gamble would be considered risk neutral (fig. 2.3). Of course, this choice is not a repeated choice; it is a one-time offer where, if you choose the gamble, you will either receive \$200 or \$0. A risk-averse individual would require the probability of winning the gamble to be higher than 0.5 before that individual would be willing to choose the gamble over the sure thing (fig. 2.3). Alternatively, a risk-seeking individual would enter the gamble for the chance of winning \$200 over taking the sure thing when the probability of winning the gamble is less than 0.5 (fig. 2.3).

In figure 2.3, the x-axis is the dollar amount received. The y-axis is the utility, or level of satisfaction, received from a specified dollar amount in the given scenario. A minimum of three points is needed to plot the utility curve. We automatically set the worst-case scenario (that is, entering the gamble and losing) to a utility of 0 and the best-case scenario (that is, entering the gamble and winning) to a utility of 1. The elicited preference probability is the utility for the third scenario (that is, choosing the sure thing). A risk-neutral person would require the probability of the winning the gamble to be 0.5 before that person felt indifferent between the choice of entering the gamble or taking the sure thing (because in this example the amount of the sure thing is the same as the expected value of the gamble). The risk-averse curve shows a person that required the probability of winning the gamble to be greater than 0.5 (0.875 in this example) before being willing to choose the

Gambling Scenario

You have a choice between taking \$100 or taking a gamble.

The gamble could result in either winning \$200 or winning \$0.

This is a different kind of gamble because you get to choose the probability of winning.

Choose the probability of winning that would cause you to view the gamble as equivalent to just walking away with the \$100.

The probability that you choose is referred to as the "preference probability" for the fixed winnings. It helps describe preference in a world with uncertainty.

Use the following interactive graph to evaluate how you feel about the preference probability.

Change the value in the highlighted cell to a probability of winning between 0 and 1.

Preference probability for a gamble versus the following gamble

To win (take \$200) 0.5
 To lose (take \$0) 0.5

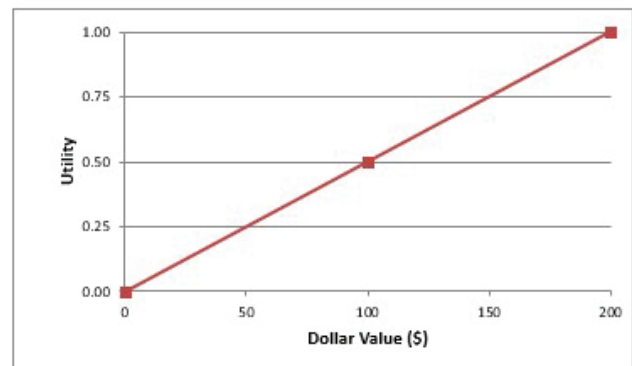
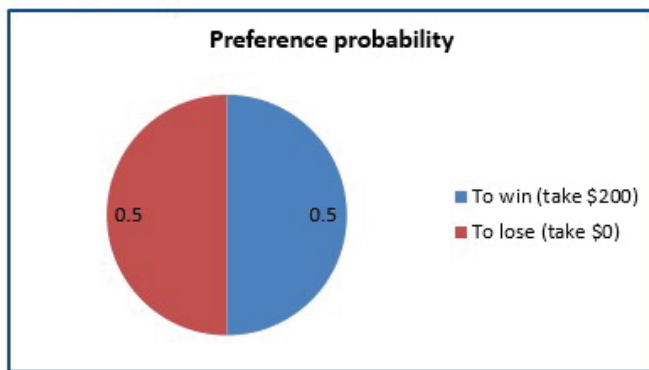


Figure 2.2. The gambling scenario set up for the practice elicitation. This was set up in a spreadsheet so that changing the preference probability in the yellow highlighted cell changed the graphs to visually see the effect on the utility curve.

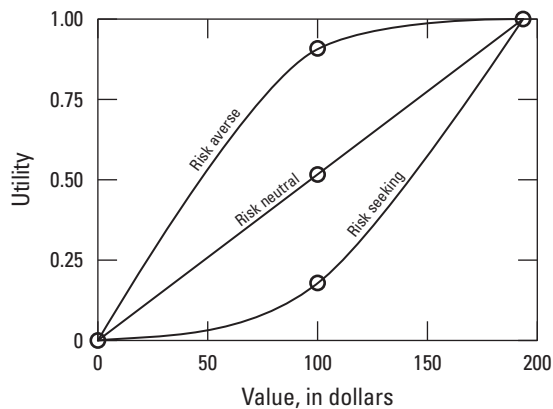


Figure 2.3. Example utility curves resulting from three different responses to the gambling question in figure 2.1.

gamble over the sure thing. The risk-seeking curve shows a person that would need the probability of winning the gamble to be less than 0.5 (0.125 in this example) before being willing to choose the gamble over the sure thing. Another way of looking at these curves is by focusing on the utility. The linear curve of the risk-neutral person reveals that this person gains equal satisfaction from each dollar won, no matter if that is an increase from \$10 to \$15 or an increase from \$75 to \$80. In comparison, the risk-adverse person is unhappy with the idea of receiving less than the amount from the sure thing and thus their satisfaction falls steeply below this value. The person is more concerned with the possibility of loss than with the potential for gains above this amount, reflected in the relatively flat curve between \$100 and \$200. The risk-seeking person is more willing to risk losing (for example, ending up with \$0) for the chance to win an amount larger than the sure thing; this person's needs are not met by the amount offered by the sure thing, and therefore, the person assigns low value to each dollar gained when the dollar amount is below this point (see the relatively flat curve between \$0 and \$100) and higher value to each dollar gained when the dollar amount is above this point (steep curve between \$100 and \$200).

Thursday, November 5, 2015: Elicitation with the HRRC

As stated earlier, this was chiefly a training exercise to verse the HRRC in this form of elicitation; the results shown below are not final.

The Elicitation

Following the same format as the practice example, we posed questions to the group regarding time to reach different levels of restoration. First, we discussed the problem to make sure everyone had a common understanding and the same assumptions. We defined the level restored by the percent area inundated by spring tides. We focused on the five subbasins affected by the Chequessett Neck Road structure: lower Herring River, mid-Herring River, lower Pole Dike Creek, Bound Brook, and upper Herring River. Given this spatial area of focus, the maximum acreage that could possibly be restored is 800 acres. Quality of restoration was assumed to reach a minimal standard; that is, an area was simply considered restored (that is, inundated by spring tides) or not restored (not inundated by spring tides). Cost of management actions was removed from consideration by assuming \$30–\$60 million had been spent.

We posed a gambling scenario for three different levels of restoration (25, 50, 75 percent) at three different time horizons (5 years, 15 years, 25 years) for a total of nine questions. We started by setting the time horizon to 5 years and setting the gambling scenario for 25 percent restored (fig. 2.4A). This is the same set up we practiced on Wednesday (fig. 1), but instead of money, we focused on percent restoration. The scenario is as follows: You have a choice of either (1) achieving

25-percent restoration (that is, 200 acres) or (2) entering a gamble where you might achieve 100-percent restoration (that is, all 800 acres) or you might achieve 0-percent restoration (that is, 0 acres). The question posed is, What probability of winning the gamble do you require in order to choose the gamble over the sure thing? We asked the same question, again given the same 5-year time horizon, but this time setting the “sure thing” to 50 percent (400 acres) restored (fig. 2.4B). We asked the question a third time, for the same 5-year time horizon, but for the “sure thing” of 75-percent (600 acres) restored (fig. 2.4C). We worked to ensure that everyone understood the question, posed the three questions to the full group of participants, and allowed the group about 5 minutes to jot down their individual answers on a piece of paper. We then went around the room, to each participant one by one, and asked them to provide their three preference probabilities. We typed the three probabilities into a spreadsheet (fig. 2.5), which was projected for the group to see; the spreadsheet was set up to show the shape of the curve that resulted from a single respondent’s three probabilities. As a group, we discussed each response. The respondent provided his/her rationale and thought process behind his/her choices, and the group provided feedback. We continued the process until we recorded the three probabilities from each of the 11 respondents. As a result of the group discussion, some respondents modified their answers. Changing of a response occurred for various reasons, some of which included (1) gaining a clearer understanding of probability, (2) gaining a better understanding of how the shape of the curve captures their risk tolerance, and (3) perceiving the situation differently after hearing and agreeing or disagreeing with another respondent’s rationale. We then repeated the process, asking for three probabilities for the three different levels of restoration but given the time horizon of 15 years. Lastly,

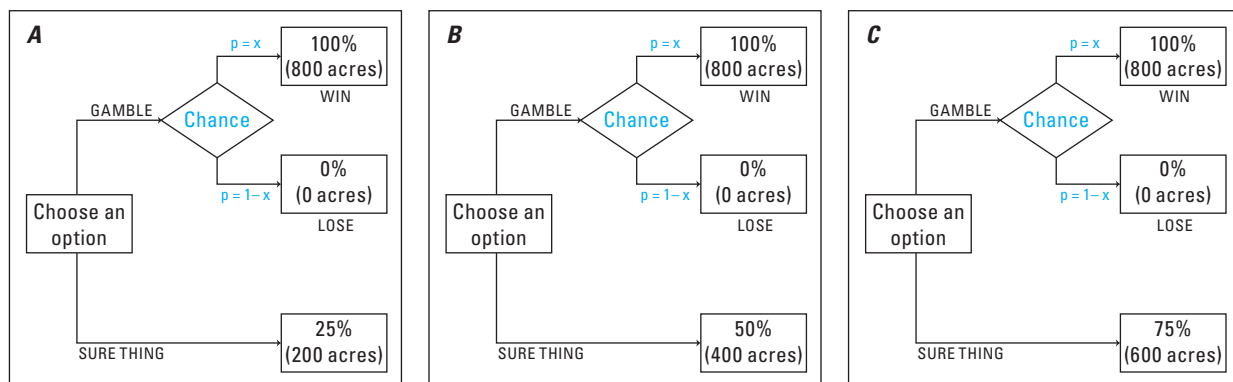


Figure 2.4. The three restoration gambling scenarios. A, You have a choice of either (1) achieving 25-percent (200 acres) restoration or (2) entering a gamble where you might achieve 100-percent (800 acres) restoration or you might achieve 0-percent (0 acre) restoration. The respondent sets the preference probability as in the practice example. B, Same question but the sure thing is 50-percent (400 acres) restoration. C, Same question but the sure thing is 75-percent (600 acres) restoration. (ac, acres; %, percent; p, probability)

Gambling Scenario

At 5 years into restoration effort, you have the choice of taking a sure thing of 25% restored (200 acres) or taking a gamble.

The gamble could result in getting the best (100% restored; 800 acres) or the worst (0% restored; 0 acres) possible levels of restoration at that point in time.

This is a different kind of gamble because you get to choose the probability of winning.

Choose the probability of winning the gamble that would cause you to view the gamble as equivalent to the sure amount restored.

The probability that you choose is termed the "preference probability" for the fixed level restored.

Use the following interactive graph to evaluate how you feel about the preference probability.

Change the value in the highlighted cells to a probability of winning between 0 and 1.

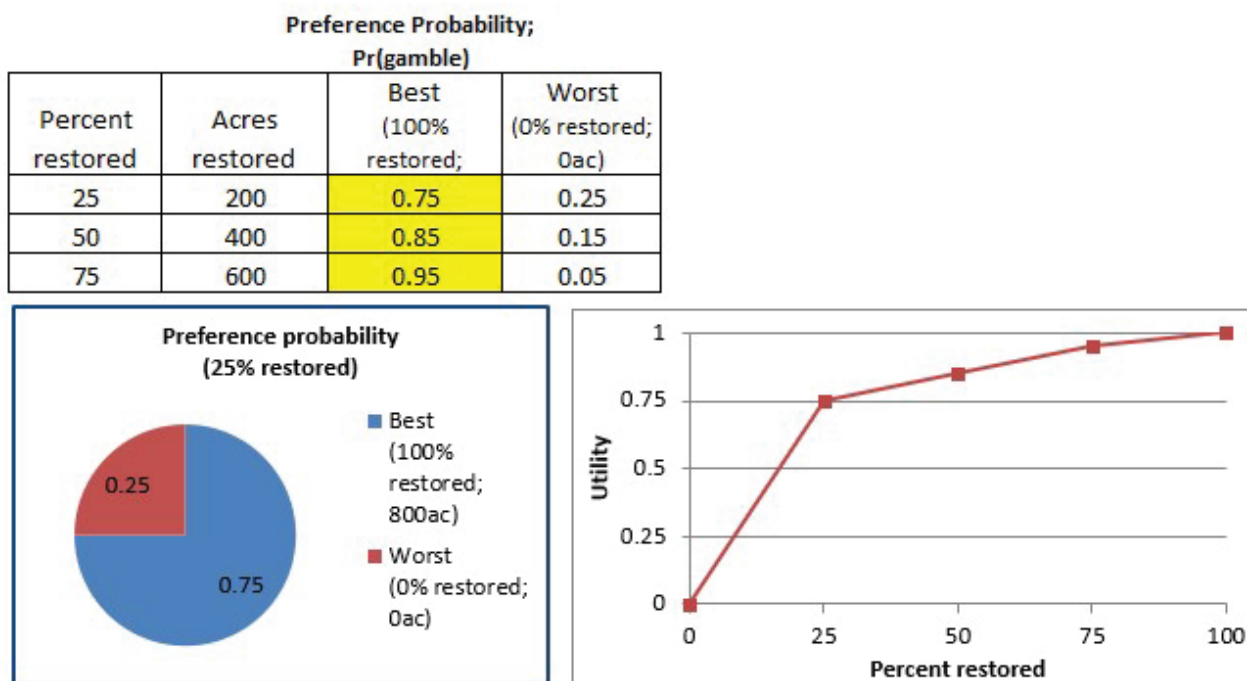


Figure 2.5. The restoration gambling scenarios shown to the respondents during the elicitation exercise. (ac, acres; %, percent)

we repeated the process under the scenario of a 25-year time horizon. After going through the process three different times, some respondents went back and modified earlier responses they had provided for different time horizons. These changes typically had to do with assessing their risk tolerance and how they perceived it changing, given their greater understanding of the different time horizons and how they felt about the level of restoration achieved at each of these time horizons. We did not capture the range of changes that a respondent provided; we captured only the final response per respondent.

In figure 2.5, the screen capture shows the response of a single respondent for the 5-year time horizon and the three different levels of restoration: 25, 50, and 75 percent. The worst case scenario (that is, entering the gamble and losing) is automatically set to a utility of 0, whereas the best case scenario (that is, entering the gamble and winning) is automatically set to a utility of 1. The elicited preference probabilities (shown in the highlighted cells) are the utility values for each level of restoration, which are also plotted in the utility curve. This is an example of a risk-averse utility curve.

Results of the Elicitation

Responses of participants are shown in table 2.1 and figures 2.6–2.9.

In figure 2.6, all respondents show risk aversion at this time horizon; that is, the preference probability has to be quite high (greater than 75% percent) for a 25-percent level of restoration. Stated another way, at 5 years into the restoration effort, people would be 75 percent satisfied with having had achieved a 25-percent level of restoration.

In figure 2.7, at a 15-year time horizon, respondents feel differently about risk (that is, differently than each other and differently than they, themselves, felt at the earlier time horizon); three respondents remain risk adverse, whereas the other respondents are more risk neutral, and a couple are tending toward risk seeking.

In figure 2.8, at a 25-year time horizon, a couple of respondents are risk adverse, but most respondents have shifted to a risk neutral or more risk-seeking behavior. The curves of the risk-seeking respondents reveal dissatisfaction

Table 2.1. Responses provided for the nine elicitation questions.

[% , percent]

Respondent	Time horizon								
	5 Years			15 Years			25 Years		
	Percent restored								
	25%	50%	75%	25%	50%	75%	25%	50%	75%
A	0.75	0.85	0.95	0.1	0.7	0.9	0.05	0.5	0.95
B	0.9	1	1	0.25	0.4	0.8	0.05	0.5	0.95
C	0.8	0.95	0.99	0.25	0.4	0.8	0.1	0.3	0.6
D	0.85	0.95	0.99	0.15	0.6	0.9	0.2	0.95	1
E	0.75	0.85	0.95	0.15	0.6	0.9	0.2	0.6	0.9
F	0.95	1	1	0.8	0.9	0.95	0.2	0.5	0.9
G	0.85	0.85	0.95	0.1	0.5	0.8	0.1	0.4	0.8
H	0.95	1	1	0.7	0.9	1	0.6	0.8	1
I	0.75	0.9	0.98	0.2	0.5	0.95	0.15	0.65	1
J	0.75	0.85	0.95	0.75	0.85	0.95	0.8	0.8	1
K	0.75	0.8	0.95	0.25	0.75	0.8	0.1	0.65	0.95

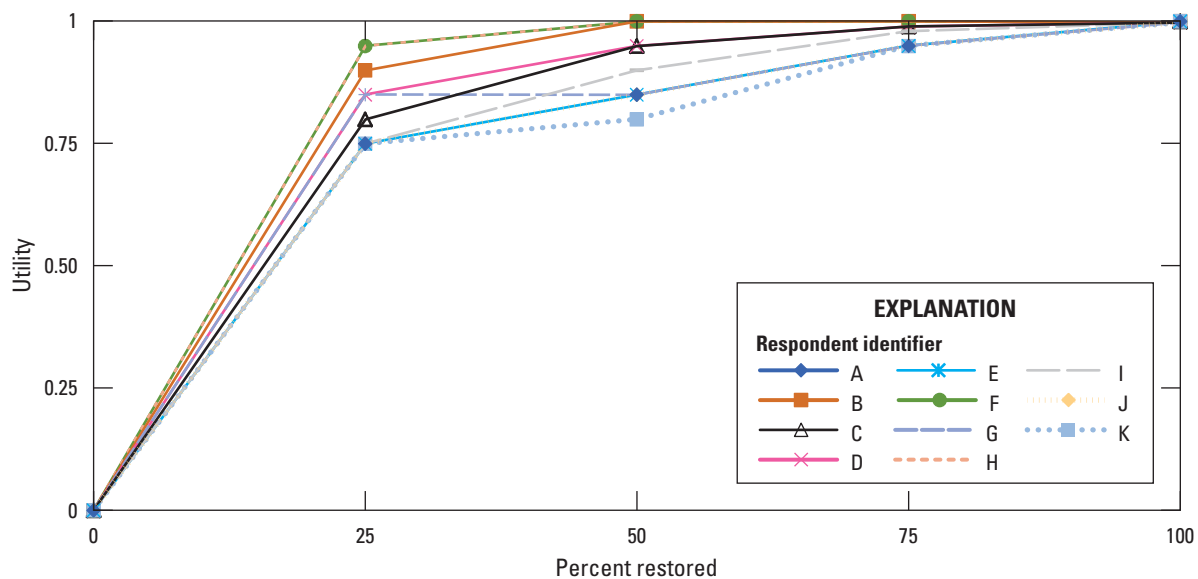


Figure 2.6. Responses of all 11 respondents for the first three questions regarding level of restoration achieved (25, 50, and 75 percent) given a 5-year time horizon.

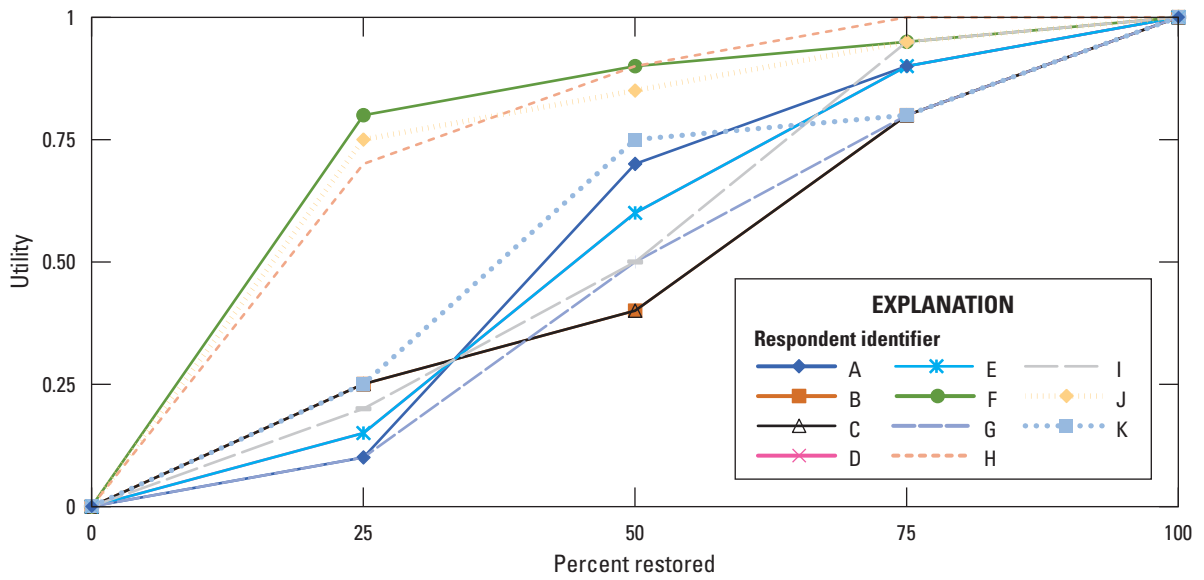


Figure 2.7. Responses of all 11 respondents for the second trio of questions regarding level of restoration achieved (25, 50, and 75 percent) given a 15-year time horizon.

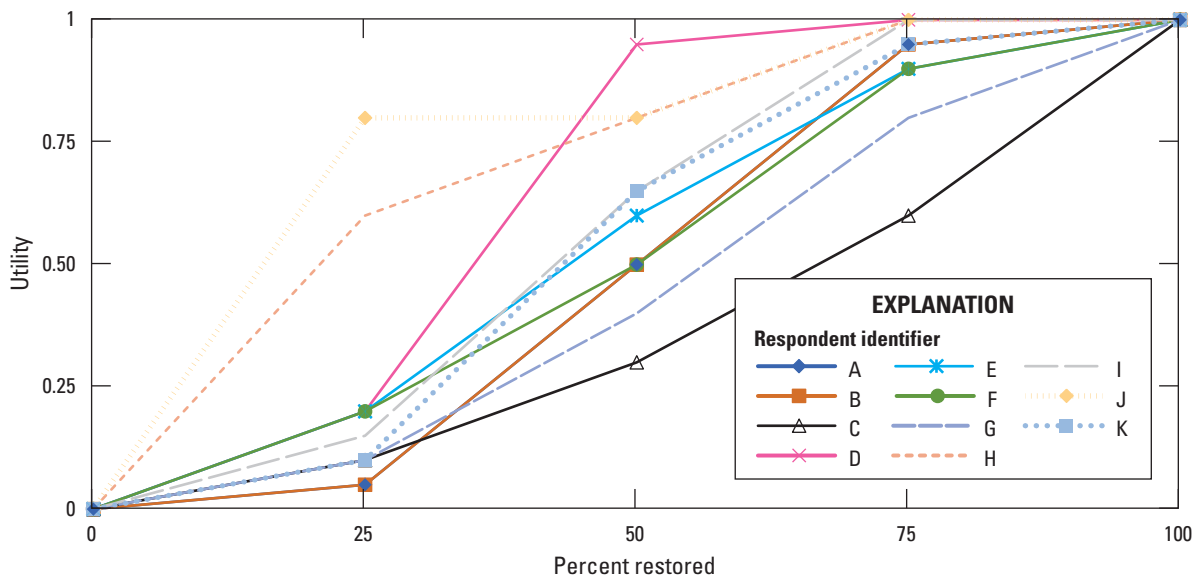


Figure 2.8. Responses of all 11 respondents for the third trio of questions regarding level of restoration achieved (25, 50, and 75 percent) given a 25-year time horizon.

with having achieved only 25-percent restoration at 25 years into the restoration effort. These respondents are so unhappy with this level of restoration, that they would be willing to gamble at a chance to achieve increased success at very low odds (ranging from 5:1 to 20:1 against). Stated another way, at 25 years into the restoration effort, most respondents are only marginally happier with 200 acres restored than they are with 0 acres restored.

In figure 2.9, all but two of the respondents shift from a risk-adverse behavior toward a risk-neutral or more risk-seeking behavior from the 5-year to the 25-year time-horizon. Two of the respondents remain risk adverse at all three time

horizons. For the two individuals who are risk adverse at all three time horizons, they would rather have something than risk having nothing, even after 25 years of working towards achieving restoration. The remaining respondents show that as the time horizon extends, their expectations of restoration levels achieved rise, such that they are dissatisfied with a low level of restoration. For most of these respondents, however, even at a 25-year time horizon, the risk-seeking behavior is confined to the lower levels of restoration (25 percent) and switches from risk neutral to risk adverse at higher levels of restoration.

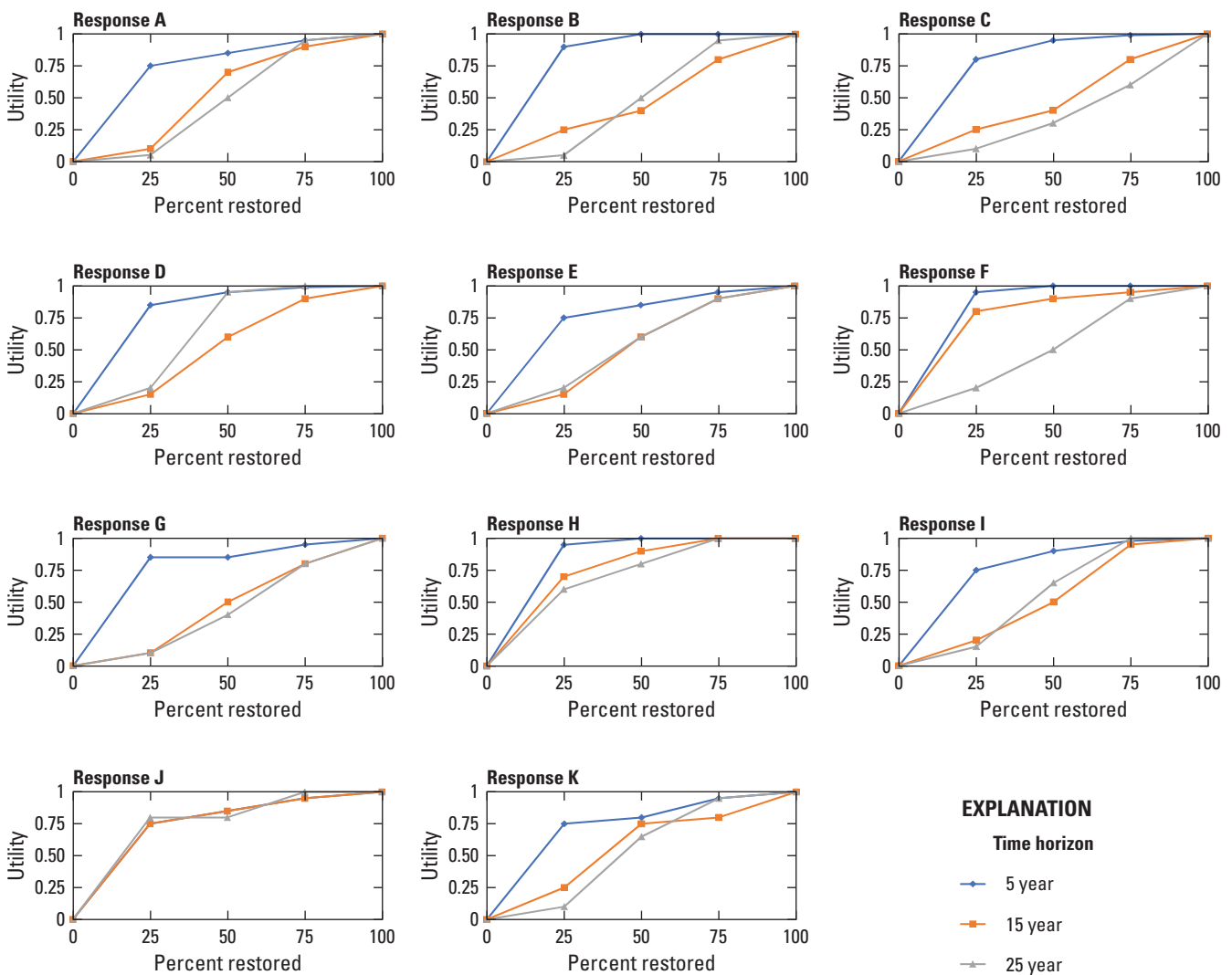


Figure 2.9. Responses to each of the three trios of questions per respondent.

How this Type of Information Will be Used?

The process would be to elicit this type of information for the restoration objectives that would be traded off each other. To follow through with this process, we would need to know the performance measure, unit, and the full potential range of each objective from its lowest to highest performance value. We would elicit utility from the decision makers. Depending on the objective, it may be appropriate to elicit this information from a stakeholder group. Elicited curves from each individual will be kept separate and, if desired, anonymous; we will use the range of the elicited values to explore the sensitivity of the decision to the differences expressed by each individual. A decision is said to be “sensitive” to the differences if one alternative option would be recommended as “best” if one utility curve was used, but a different alternative option would be “best” if another curve was used. If the decision is not sensitive to the differences (that is, the same alternative option would be recommended regardless of the different curves), then we can decide whether and how to combine the responses across individuals for a single objective. If the decision is sensitive to the differences, then some form of negotiation would have to take place to select among the identified alternative policies that are in contention.

Values from these curves, which we refer to as “utility,” will be used in the consequence table in place of the actual predicted outcomes (that is, they represent the “true value” of any particular outcome). Imagine a two-step process. In the first step, we populate a consequence table with the raw predicted values of the outcomes of each objective, in terms of its performance measure, for each alternative action/decision that is under consideration. In the second step, we convert the raw predicted values into their respective utility, based on the curves we elicited. In doing so, the consequence table will be capturing two aspects: (1) the prediction, which is based on the best available science and (2) values, which are based on how decision makers/stakeholders feel about the predicted outcomes.

Why do we want to use “utility” as opposed to the raw predictions in the consequence table?

Often, our feelings about outcomes are not linear; that is, we do not feel the same about an x unit increase in an objective across the full range of the potential outcomes of that objective. For example, if the objective is to minimize cost, the decision makers may not care that much about a difference in cost of \$10 million among alternative actions if one decision costs \$5 million and the other costs \$15 million; however, decision makers might feel quite differently about the same \$10 million difference between alternative actions if the costs of the two options were \$60 million and \$70 million

(fig. 2.10). When assessing performance of alternative actions across an objective, what matters is how the decision maker feels about the predicted outcome, not the predicted outcome itself. This is part of value-focused decision making; we focus on what we care about (objectives), and we focus on the level of satisfaction with the predicted outcomes (utility) for these objectives.

How does all the information come together to help us identify the decision that performs best across the project objectives?

Imagine a consequence table that is populated with the predicted outcomes for all objectives across each of the decision alternatives under consideration. Also, imagine we have the utility curves for each of the objectives. We then determine the utility of the predicted outcomes of each objective across each decision alternative. We then sum the utility values across all objectives for each decision alternative. Another step, the process of which is not described here, is weighting of the different objectives (stated simply, not all objectives are valued equally). The weights for the different objectives will result in a weighted sum of the utilities for each decision alternative. We compare the weighted sum of utilities for each decision alternative; the alternative with the highest weighted sum is the alternative that performs best across the objectives. Below is a contrived example of the generic description above; to keep it simple, the example considers three objectives and two decision alternatives.

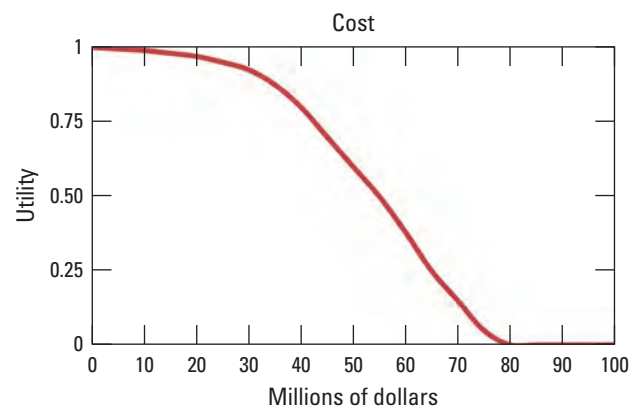
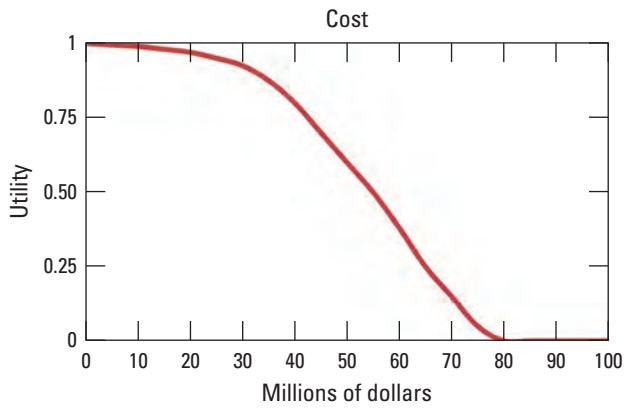
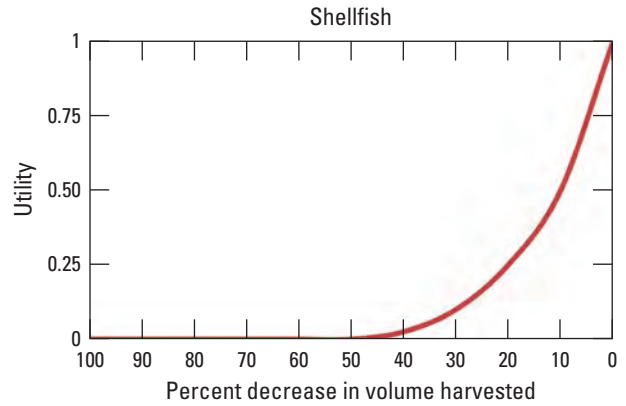
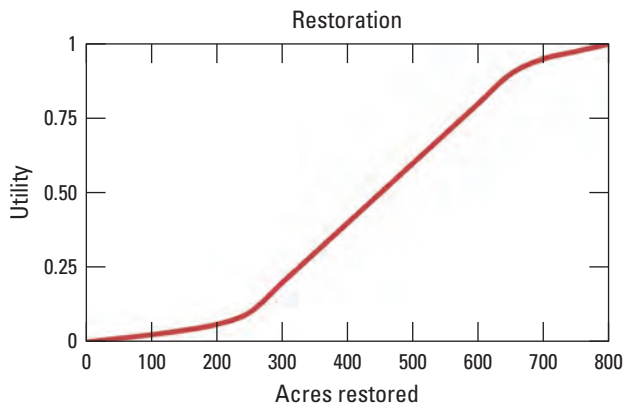


Figure 2.10. Example non-linear utility curve for cost. In this scenario, the decision maker has high satisfaction with spending \$0–30 million; however, the level of satisfaction decreases quickly with spending beyond \$30 million, declining to 0 at the point of \$80 million.

40 A Decision Framework to Analyze Tide-Gate Options for Restoration of the Herring River Estuary, Massachusetts

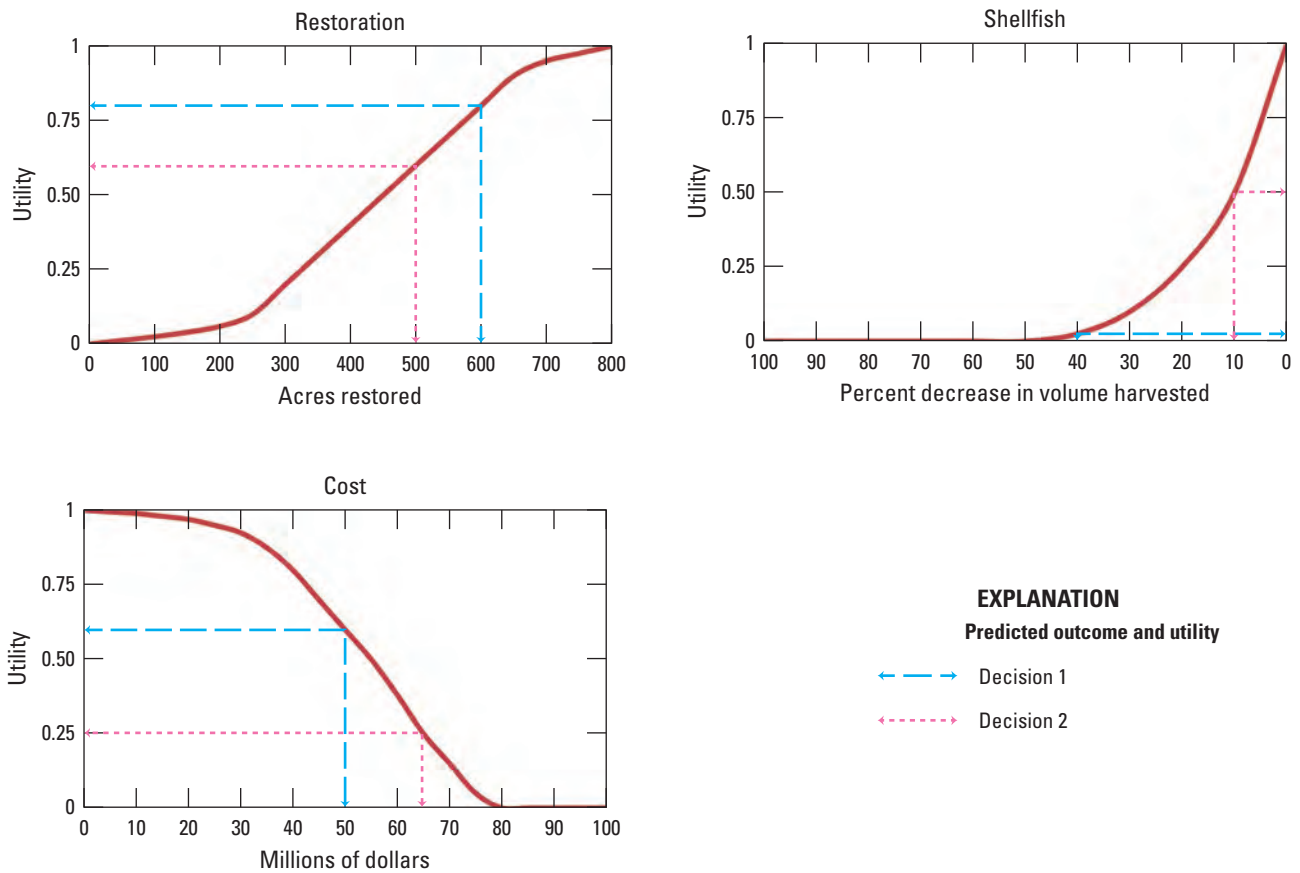
Step 1. Elicit utility curves for the three objectives.



Step 2. Populate the consequence table with the raw predicted outcomes.

Objectives	Unit	Direction	Decision 1	Decision 2
Restoration	Acres restored	Maximize	600	500
Shellfish	Percent decrease in volume harvested	Minimize	40	10
Cost	Millions of dollars	Minimize	50	65

Step 3. Determine the utility associated with each predicted outcome.



Step 4. Populate the consequence table with the utilities from the elicited curves.

Because we are now using utilities as opposed to the raw predictions, we want to maximize utility in all cases. Specifically, though we wish to minimize the percent decrease in the volume of shellfish harvested and minimize the cost, we wish to maximize the utility for these objectives.

Objectives	Unit	Direction	Decision 1	Decision 2
Restoration	Acres restored	Maximize	0.8	0.6
Shellfish	Percent decrease in volume harvested	Minimize (unit)	.025	0.5
		Maximize (utility)		
Cost	Millions of dollars	Minimize (unit)	0.6	0.25
		Maximize (utility)		

Step 5. Calculate a weighted sum of utilities across objectives for each alternative decision.

$$U_1 = w_r(u_{r1}) + w_s(u_{s1}) + w_c(u_{c1})$$

$$U_2 = w_r(u_{r2}) + w_s(u_{s2}) + w_c(u_{c2})$$

where

U	= sum of utilities across all objectives,
u	= utility of individual objectives,
w	= weight on the objective,
r	= restoration objective,
s	= shellfish objective, and
c	= cost objective.

Subscripts 1 and 2 are for decision alternatives 1 and 2.

Assuming equal weight for each of the three objectives, the calculation for this example would be as follows:

$$U_1 = (0.8) + (0.025) + (0.6) = 0.475 \text{ and}$$

$$U_2 = (0.6) + (0.5) + (0.25) = 0.45.$$

U_1 is greater than U_2 ; therefore, Decision 1 performs best across the objectives.

Given everyone agreed with the input, the recommendation would be to go with decision alternative 1. Recall, the input to arrive at this weighted utility score includes the following pieces: (1) choice of objectives, including their performance measures; (2) elicitation of utility curves for each objective; (3) creation of alternative decisions under consideration; (4) predicted outcomes of each alternative with respect to each objective; and (5) weights on each objective. Changes to any one of these inputs may result in a different decision outcome. In an additional analysis, we can explore the sensitivity of the decision to uncertainty or disagreement regarding the utility curves, the predicted outcomes, and the weights on the objectives. We can only evaluate the objectives and the alternatives that have been developed for consideration; thus, it is important that these have been fully vetted beforehand.

Insights from the Elicitation Exercise

1. Set up matters. Though we spent a fair amount of time preparing the elicitation, including choice of objectives on which to focus, the spatial scale, the range of potential outcomes for the objectives, and the methods of elicitation, once the group convened, discussion regarding these choices was essential and affected the procedure.
2. You can never be too clear. Though we knew that it is imperative for everyone to have a common understanding of the assumptions, the process, and the questions, despite taking precautions to ensure everyone was on the same page, different interpretations cropped up. Thus, it is important to be vigilant, in communicating and in listening, to identify potential different interpretations of the question that could bias the results.
3. How questions are phrased has potential to introduce bias. For example, the primer on Wednesday evoked quite a different response from participants depending on how it was phrased. If the question was phrased as “You just won \$100; now you have a choice to keep it or enter a gamble where you can either double it or lose it all,” it was perceived very differently than if phrased as, “You have \$100 in your pocket that is your existing, earned money; you have a choice to keep your money or enter a gamble where you can double it or lose it all.” The distinction regarding whether the \$100 had been won (that is, essentially free money) versus earned made a big difference in participants risk tolerances. It is critical that we are aware of these types of biases when phrasing future elicitations regarding project objectives.
4. The shape of participants’ curves may differ because of who the person represents. For example, one participant explained that he was answering the questions as a representative of the townspeople. He expressed that 25-percent restoration achieved at 25 years into the restoration effort would be completely unacceptable to the townspeople; as such, he was willing to risk obtaining 25-percent restoration for a small chance at achieving a much higher success.
5. There is a balance between the number of questions we ask and the quality of the information we receive. Too many questions will quickly lead to fatigue in the participants. Too few questions may not provide the detail of information we require. For example, it took about 2 hours for us to complete the nine questions for the one objective with the group. Even so, it was noted by a participant that we needed finer discretization of the percent restored to determine more accurately the inflexion point of the curves. Finer discretization of either component (that is, percent restored or years of restoration effort) quickly increases the number of questions we must ask. We will always need to keep this balance in mind when we develop elicitations in the future for all the objectives.

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