Integrated Wetland Management for Waterfowl and Shorebirds at Mattamuskeet National Wildlife Refuge, North Carolina

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U.S. Department of the Interior
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Cover: Photo of Northern Pintail feeding at Mattamuskeet National Wildlife Refuge (Photograph by Mike Dunn).

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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)
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047.0	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
acre-foot (acre-ft)	1,233.0	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)

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By Brian G. Tavernia,[1] John D. Stanton,[2] and James E. Lyons[1]

Abstract

Mattamuskeet National Wildlife Refuge (MNWR) offers a mix of open water, marsh, forest, and cropland habitats on 20,307 hectares in coastal North Carolina. In 1934, Federal legislation (Executive Order 6924) established MNWR to benefit wintering waterfowl and other migratory bird species. On an annual basis, the refuge staff decide how to manage 14 impoundments to benefit not only waterfowl during the nonbreeding season, but also shorebirds during fall and spring migration. In making these decisions, the challenge is to select a portfolio, or collection, of management actions for the impoundments that optimizes use by the three groups of birds while respecting budget constraints. In this study, a decision support tool was developed for these annual management decisions.

Within the decision framework, there are three different management objectives: shorebird-use days during fall and spring migrations, and waterfowl-use days during the nonbreeding season. Sixteen potential management actions were identified for impoundments; each action represents a combination of hydroperiod and vegetation manipulation. Example hydroperiods include semi-permanent and seasonal drawdowns, and vegetation manipulations include mechanical-chemical treatment, burning, disking, and no action. Expert elicitation was used to build a Bayesian Belief Network (BBN) model that predicts shorebird- and waterfowl-use days for each potential management action. The BBN was parameterized for a representative impoundment, MI-9, and predictions were re-scaled for this impoundment to predict outcomes at other impoundments on the basis of size. Parameter estimates in the BBN model can be updated using observations from ongoing monitoring that is part of the Integrated Waterbird Management and Monitoring (IWMM) program.

The optimal portfolio of management actions depends on the importance, that is, weights, assigned to the three objectives, as well as the budget. Five scenarios with a variety of objective weights and budgets were developed. Given the large number of possible portfolios (16^{14}), a heuristic genetic algorithm was used to identify a management action portfolio that maximized use-day objectives while respecting budget constraints. The genetic algorithm identified a portfolio of management actions for each of the five scenarios, enabling refuge staff to explore the sensitivity of their management decisions to objective weights and budget constraints.

The decision framework developed here provides a transparent, defensible, and testable foundation for decision making at MNWR. The BBN model explicitly structures and parameterizes a mental model previously used by an expert to assign management actions to the impoundments. With ongoing IWMM monitoring, predictions from the model can be tested, and model parameters updated, to reflect empirical observations. This framework is intended to be a living document that can be updated to reflect changes in the decision context (for example, new objectives or constraints, or new models to compete with the current BBN model). Rather than a mandate to refuge staff, this framework is intended to be a decision support tool; tool outputs can become part of the deliberations of refuge staff when making difficult management decisions for multiple objectives.

Introduction

Mattamuskeet National Wildlife Refuge (MNWR) in coastal North Carolina provides a mix of open water, marsh, forest, and croplands on 20,307 hectares (ha), but the largest fraction, 16,227 ha, consists of Lake Mattamuskeet (80%) (https://www.fws.gov/mattamuskeet; fig. 1). Executive Order 6924 established the refuge in 1934 to provide habitat for wintering waterfowl, and the refuge's importance to waterfowl is widely recognized. For example, as much as 80 percent of *Anas acuta* (northern pintail) in the Atlantic Flyway use the refuge during part of their annual cycle (J.D. Stanton, U.S. Fish and Wildlife, unpub. data, 2014).

Executive Order 6924 indicates that management at the refuge should benefit other migratory bird species in addition to waterfowl. The southeastern Coastal Plains–Caribbean

[1] U.S. Geological Survey.
[2] U.S. Fish and Wildlife Service.

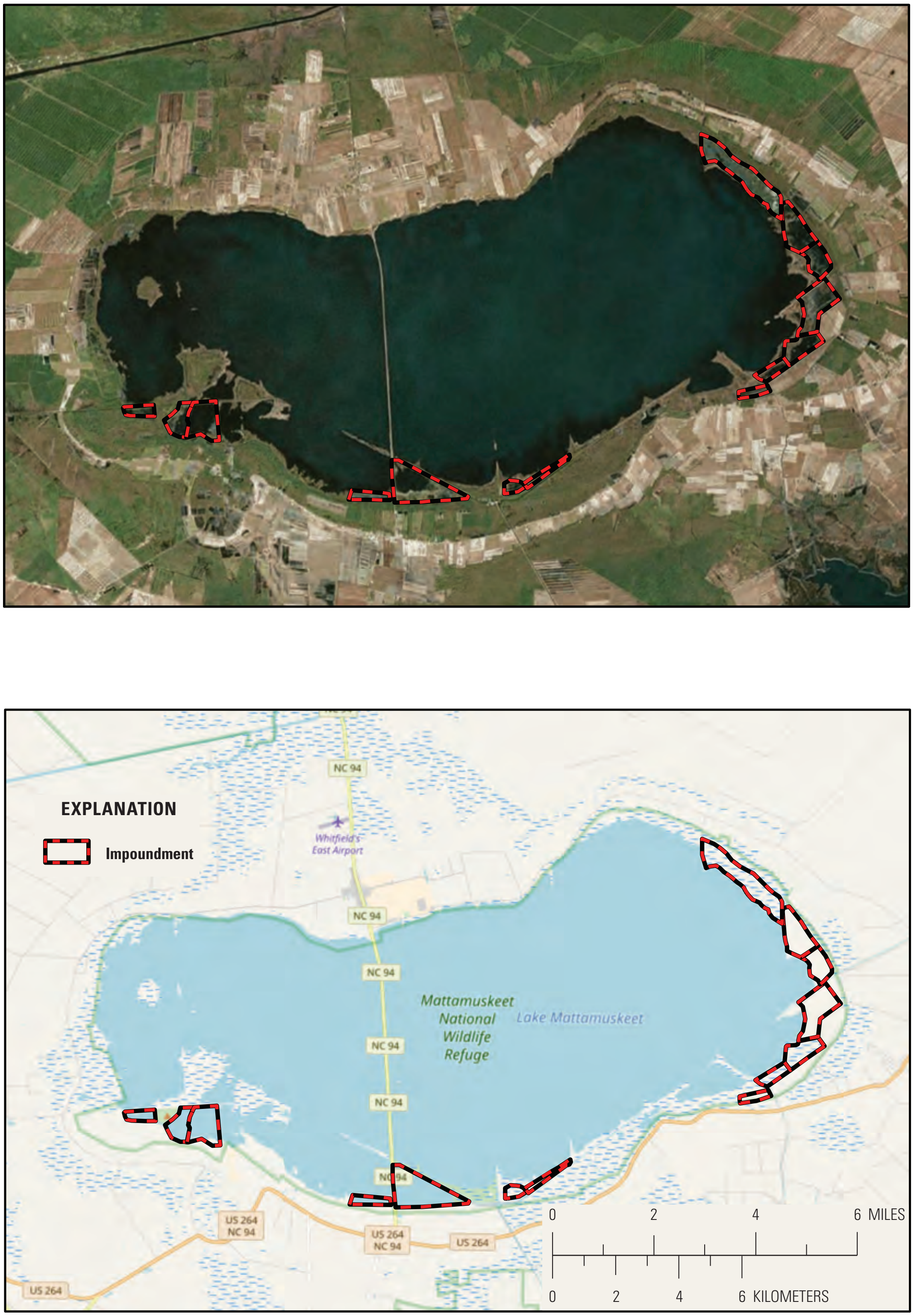

Figure 1. Aerial and atlas maps of Mattamuskeet National Wildlife Refuge, North Carolina, 35° 27´ to 35° 34´ N and from 76° 3´ to 76° 19´. Data Sources: © OpenStreetMap (and) contributors; Farm Service Agency, U.S. Department of Agriculture

Region Shorebird Conservation Plan (Hunter and others, 2002) assessed habitat objectives for migrating shorebirds in the southeastern coastal plains of the Atlantic Flyway and established interim habitat objectives for spring and fall migration. The plan's habitat objectives led managers at the MNWR to explicitly consider spring and fall shorebird migration in habitat management decisions. Thus, MNWR strives to optimize use by non-breeding waterfowl and migrating shorebirds while recognizing that the primary purpose of the refuge is to provide habitat for wintering waterfowl.

Fourteen freshwater impoundments ring the perimeter of Lake Mattamuskeet (fig. 1), and the refuge manages these impoundments to provide high quality foraging and resting habitat by manipulating water levels and vegetation communities (U.S. Fish and Wildlife Service, 2008). Annually, MNWR managers decide on the collective management of these impoundments to provide suitable, high quality habitat for non-breeding waterfowl and for shorebirds during fall and spring migration. These annual habitat management decisions are assumed to affect the fitness and subsequent population status of waterfowl and shorebirds within the Atlantic Flyway.

Several factors constrain the management actions implemented within the impoundments. Financial and staff labor resources limit the number and types of management actions, especially actions that are resource intensive (for example, disking an impoundment to set back succession). The seasonal availability of water resources and the need to respect the drainage rights of surrounding landowners can constrain water-level manipulations.

An annual management plan is developed in late winter/early spring each year by MNWR management, including the Refuge Manager, Deputy Refuge Manager, and Refuge Biologist. This plan is informed by the condition of vegetation during the previous fall survey (that is, composition and quality), results of the previous year's mechanical and chemical treatments, and counts of non-breeding waterfowl and migratory shorebirds using individual impoundments. The plan applies to all 14 impoundments in the MNWR.

Purpose and Scope

This report develops a decision framework to support integrated wetland management for nonbreeding waterfowl and migrating shorebirds at MNWR. Management objectives are defined for use-days by nonbreeding waterfowl and shorebirds during their fall and spring migrations. Management actions are defined using vegetation manipulations and hydroperiods and linked to objectives through a quantitative, predictive model developed through expert elicitation. A genetic algorithm is used to select a portfolio of management actions, and the sensitivity of the selected portfolio to different objective weights and budgetary constraints is explored. Potential future revisions to and enhancements of the decision framework are presented to address changes to the decision context (for example, different budgetary constraints) and sources of uncertainty (for example, competing predictive models).

Objectives

The waterfowl objective of this study was

1. Maximize the number waterfowl-use days during the non-breeding season (September 15–March 15) for all impoundments.

The following waterfowl species are known to stop over during migration or overwinter and utilize the impoundments at MNWR: *Aix sponsa* (wood duck), *Anas acuta* (northern pintail), *Anas americana* (American wigeon), *Anas clypeata* (northern shoveler), *Anas crecca* (green-winged teal), *Anas discors* (blue-winged teal), *Anas platyrhynchos* (mallard), *Anas rubripes* (American black duck), *Anas strepera* (gadwall), *Aythya collaris* (ring-necked duck), *Branta canadensis* (Canada goose), *Chen caerulescens* (snow goose), *Cygnus columbianus* (tundra swan), and *Lophodytes cucullatus* (hooded merganser).

The shorebird objectives were

1. Maximize the number shorebird-use days during spring migration (March 15–June 1) for all impoundments, and

2. Maximize the number shorebird-use days during fall migration (July 15–November 15) for all impoundments.

Shorebird species that forage and rest in shallow water and mudflat habitats found within the impoundments at MNWR during spring and fall migration include *Actitis macularius* (spotted sandpiper), *Calidris alpina* (dunlin), *Calidris mauri* (western sandpiper), *Calidris minutilla* (least sandpiper), *Calidris pusilla* (semipalmated sandpiper), *Charadrius semipalmatus* (semipalmated plover), *Charadrius vociferus* (killdeer), *Gallinago delicata* (Wilson's snipe), *Limnodromus griseus* (short-billed dowitcher), *Limnodromus scolopaceus* (long-billed dowitcher), *Tringa flavipes* (lesser yellowlegs), *Tringa melanoleuca* (greater yellowlegs), and *Tringa solitaria* (solitary sandpiper).

Waterfowl- and shorebird-use day objectives are differentially weighted in the refuge's decision-making process. When evaluating management alternatives for impoundments, given a fixed budget, we examined the sensitivity of our analyses to different weighting schemes for these objectives (see the "Tradeoffs Using Portfolio Analysis" section).

Alternatives

The alternatives for this decision framework consist of different portfolios, or collections, of individual management actions for each of the 14 impoundments at MNWR.

Management actions at individual impoundments are defined by a specific combination of vegetation manipulation and hydroperiod. In following sections, individual vegetation manipulations and hydroperiods are defined, and 16 combinations used to manage impoundments are listed. A glossary of terms used to define hydroperiods can be found in appendix 1; terms defined in appendix 1 are in bold font in this report. Following the description of vegetation manipulations and hydroperiods, two examples of management action portfolios are provided.

Vegetation Manipulations

Vegetation manipulations are of three types—mechanical-chemical, burn, or disk (table 1). The mechanical-chemical and burn manipulations represent aggregations of more specific management actions (for example, mechanical roller-chop). Shorebird and waterfowl responses are expected to differ to a greater degree across the aggregate mechanical-chemical and burn manipulations than across their constituent vegetation manipulations. Consequently, the decision analytic process focused on the aggregate manipulations.

The implementation of vegetation manipulations requires different levels of technical expertise. Refuge personnel have the ability to implement mechanical-chemical and disking manipulations; a specialized group is used to carry out prescribed burns.

Hydroperiods

1. Semi-permanent (SEMI; fig. 2).

The impoundment remains relatively constant at full pool year round although water levels may fluctuate naturally during the summer owing to evapotranspiration and rainfall. Periodic drawdowns to ditch top or below ditch top are used to control undesirable vegetation, promote nutrient cycling, or make repairs to infrastructure. Such drawdowns occur once every 3 to 10 years (or as needed). Once vegetation manipulations or infrastructure repairs are complete, the impoundment is re-flooded to full pool and maintained at full pool. Semi-permanent impoundments can be shifted to seasonally managed impoundments if a change in the habitat state is desired.

2. Early summer drawdown to ditch top (ESDT; fig. 3).

From January 1 through early April, the impoundment is maintained at full pool. A drawdown is conducted from early April through early May, terminating when the water reaches ditch top. The impoundment is maintained at ditch-top condition through early October, then is gradually flooded to full pool by mid-November.

3. Early summer drawdown to below ditch top (ESBDT; fig. 3).

From January 1 through early April, the impoundment is maintained at full pool. A drawdown is conducted from early April through early May, terminating when water levels are

Table 1. Definitions of three vegetation manipulations implemented in impoundments at Mattamuskeet National Wildlife Refuge, North Carolina.

1. **Mechanical-chemical:** Effectively manipulates vegetation by reducing monocultures of robust plants. This reduces woody invasion in moist-soil areas and modifies vegetation structure (Fredrickson and Reid, 1988). Mechanical-chemical is an aggregate of more specific manipulations, including:
   - **Roller-chop:** Use of an agricultural tractor or bulldozer and roller-chopper to crush undesired vegetation.
   - **Mow:** Use of tractor and bush-hog or flail mower to mow undesirable vegetation.
   - **Chemical treatment:** Herbicides are applied according to label directions to kill undesirable vegetation. They are applied through sprayers or applied by a contractor through aerial applicators approved for herbicide application.
2. **Burn:** Effectively manipulates vegetation by reducing monocultures of robust plants. This reduces woody invasion in moist-soil areas and modifies vegetation structure (Fredrickson and Reid, 1988). Burning facilitates nutrient cycling and can lead to more diverse vegetation communities and vigorous growth. Burn is an aggregate of more specific manipulations, including:
   - **Mow and Burn:** A tractor and bush-hog or flail mower is used to mow undesirable vegetation, and if necessary, firebreaks are installed. Mowed vegetation is allowed to dry, and a prescribed fire is then conducted.
   - **Prescribed Burn:** Vegetation is allowed to become senescent or die back, and a prescribed burn is conducted. Firebreaks are installed through disking, if necessary.
3. **Disk:** Effectively manipulates vegetation by setting back succession and increasing diversity of monotypic plant communities with undesirable characteristics (Fredrickson and Reid, 1988):
   - A tractor and agricultural disk are used to make a few passes across the impoundment, breaking the soil to an average depth of 5–10 inches.

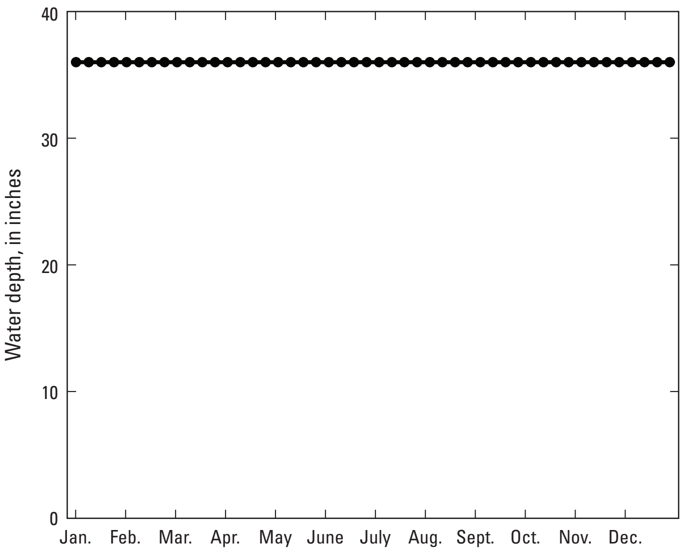

Figure 2. Semi-permanent hydroperiod for an impoundment at Mattamuskeet National Wildlife Refuge, North Carolina.

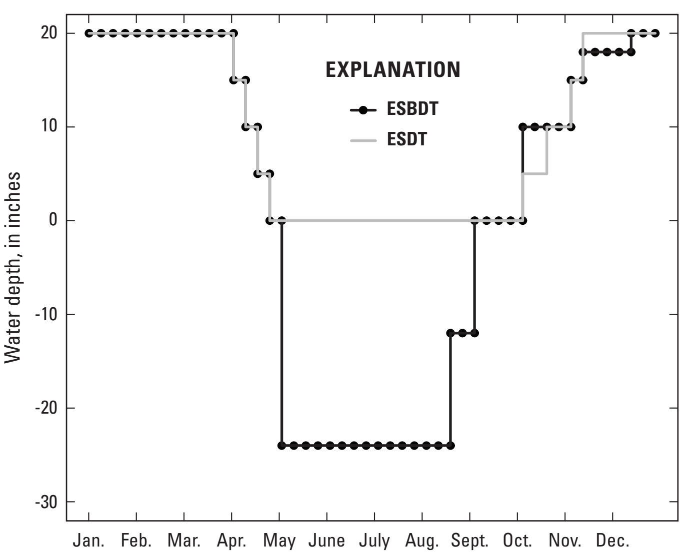

Figure 3. Hydroperiods corresponding to early summer drawdowns to ditch-top (ESDT) or below-ditch-top (ESBDT) conditions for an impoundment at Mattamuskeet National Wildlife Refuge, North Carolina.

below ditch top. Water levels are maintained at below-ditch-top condition through pumping (as needed) until mid-August when flooding begins. The impoundment achieves full pool by mid-December.

4. Late summer drawdown to ditch top (LSDT; fig. 4).

Beginning January 1, the impoundment is maintained at full pool until March, then the water level is allowed to fluctuate naturally (that is, from evapotranspiration or rainfall) from March through early June. From early June through early July, a gradual drawdown is conducted, terminating when the water level reaches ditch top. Ditch-top conditions are maintained

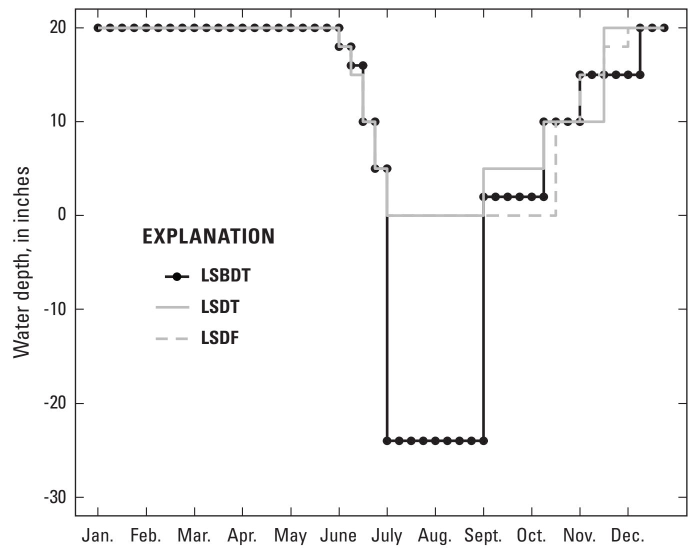

Figure 4. Hydroperiods corresponding to late summer drawdowns to ditch-top condition (LSDT), ditch top with a delayed flood (LSDF), and below-ditch-top condition (LSBDT) for an impoundment at Mattamuskeet National Wildlife Refuge, North Carolina.

until early September when gradual flooding begins. Flooding results in full pool by November.

5. Late summer drawdown to ditch-top condition and delayed flood (LSDF; fig. 4).

Beginning January 1, the impoundment is maintained at full pool until March, then the water level is allowed to fluctuate naturally (that is, from evapotranspiration or rainfall) from March through early June. The impoundment is gradually drawn down from early June through early July, terminating when ditch-top condition is reached. Ditch-top condition is maintained through pumping (as needed) until late October when gradual flooding begins. The impoundment reaches full pool by early December.

6. Late summer drawdown to below-ditch-top condition (LSBDT; fig. 4).

Beginning January 1, the impoundment is maintained at full pool until March, then the water level is allowed to fluctuate naturally (that is, from evapotranspiration or rainfall) from March through early June. The impoundment is gradually drawn down from early June through early July, terminating when water levels are below ditch top. The water level is maintained below ditch top through pumping (as needed) until September, then the impoundment is gradually flooded, reaching full pool in early December.

7. Early drawdown, flood, late drawdown, and re-flood (EFLR; fig. 5).

From January 1 through early March, the impoundment is maintained at full pool. A gradual drawdown is conducted from early March through April 1, ending when the water level is at ditch top. The impoundment is maintained at ditch

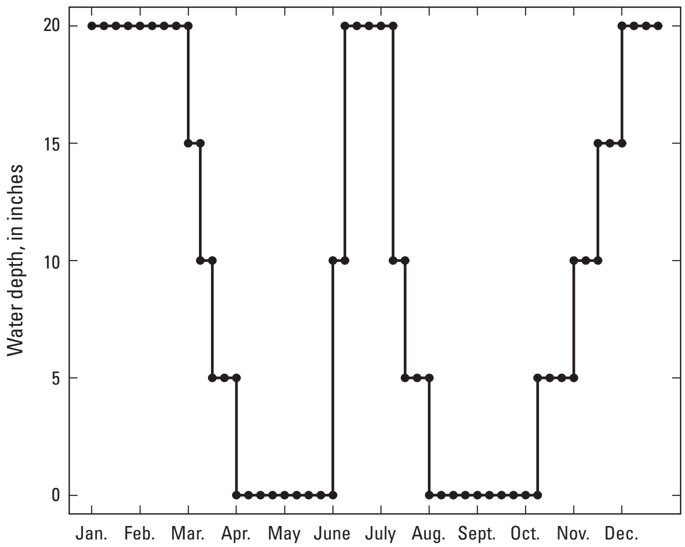

Figure 5. Hydroperiod corresponding to an early drawdown, flood, late drawdown, and subsequent re-flood for an impoundment at Mattamuskeet National Wildlife Refuge, North Carolina.

top until June 1, then flooded to full pool by June 15. The impoundment is maintained through pumping (as needed) at full pool until July 15.

Between July 15 and August 1, a second drawdown occurs, resulting in a ditch-top condition. Ditch-top condition is maintained until October 15, then the impoundment is gradually re-flooded to full pool by December 1 by precipitation. Active pumping is used if necessary to reach full pool.

Management Actions: Combining Vegetation Manipulation and Hydroperiod

The ability to carry out particular vegetation manipulations depends on the current hydroperiod and habitat conditions. For example, disking requires a hydroperiod that includes water levels below ditch top; it is only when the water level is below ditch top that a wetland becomes dry enough for a tractor and disk to be used. Consequently, only 16 combinations of hydroperiod and vegetation manipulations are possible, hereafter referred to as “management actions” (table 2).

Management Action Portfolios

For the decision analysis, alternatives were defined by management action portfolios; a portfolio is a combination of 14 management actions—one for each managed unit. For illustration purposes, table 3 offers two example portfolios. With 14 impoundments and 16 potential management actions (table 2), the number of possible portfolios is approximately 7.2×10^{16}. As described later (appendix 6), we used a genetic algorithm to evaluate possible portfolios and identify the preferred option given our management objectives and constraints.

Table 2. Sixteen wetland management actions used in the decision analysis, Mattamuskeet National Wildlife Refuge, North Carolina.

[Management actions are combinations of hydroperiod and vegetation manipulation. Recommended timing indicates when vegetation manipulation is typically applied. Costs are determined by the size of the impoundment (see appendix 7). For illustration purposes, costs are shown for impoundment MI-9. N/A, not applicable]

Action number	Hydroperiod	Hydroperiod abbreviation	Vegetation manipulation	Recommended timing of vegetation manipulation	Cost ($)
1	Semi-permanent	SEMI	None	N/A	210
2			Mechanical-chemical	March 1–August 15	8,279
3	Early summer drawdown to ditch top	ESDT	None	N/A	350
4	Early summer drawdown to below ditch top	ESBDT	None	N/A	1,260
5			Mechanical-chemical	May 15–August 15	9,329
6			Burn	July 1–15 August	9,238
7			Disk	May 15–August 15	5,147
8	Late summer drawdown to ditch top	LSDT	None	N/A	210
9	Late summer drawdown to ditch top and delayed flood	LSDF	None	N/A	8,781
10			Mechanical-chemical	July 15–October 15	16,850

Table 2. Sixteen wetland management actions used in the decision analysis, Mattamuskeet National Wildlife Refuge, North Carolina.—Continued

[Management actions are combinations of hydroperiod and vegetation manipulation. Recommended timing indicates when vegetation manipulation is typically applied. Costs are determined by the size of the impoundment (see appendix 7). For illustration purposes, costs are shown for impoundment MI-9. N/A, not applicable]

Action number	Hydroperiod	Hydroperiod abbreviation	Vegetation manipulation	Recommended timing of vegetation manipulation	Cost ($)
11	Late summer drawdown to below ditch top	LSBDT	None	N/A	1,050
12			Mechanical-chemical	July 1–August 15	9,119
13			Burn	July 15–September 1	9,028
14			Disk	July 1–September 1	4,937
15	Early summer drawdown, flood, late summer draw-down, re-flood	EFLR	None	N/A	9,061
16			Mechanical-chemical	April 1–June 1 and August 1–October 15	17,130

Table 3. Two example management action portfolios for the 14 managed impoundments at Mattamuskeet National Wildlife Refuge, North Carolina.

[Hydroperiod abbreviations are defined in table 2]

Impoundment	Hectares	Non-breeding waterfowl portfolio example	Migrating shorebird portfolio example
MI-1	30.5	SEMI No action	SEMI Mechanical-chemical
MI-2W	58.2	ESBDT Disk	ESDT No action
MI-2E	103.4	EFLR No action	EFLR No action
MI-3	31.6	SEMI No action	SEMI Mechanical-chemical
MI-4	184.1	LSBDT Disk	LSDT No action
MI-5	20.7	LSBDT Mechanical-chemical	LSBDT Burn
MI-6	23.6	ESBDT Disk	ESBDT Mechanical-chemical
MI-7	22	ESDT No action	EFLR No action
MI-8W	34.5	ESBDT Mechanical-chemical	LSBDT Mechanical-chemical
MI-8E	69.6	ESBDT Disk	ESDT No action
MI-9	121.1	ESBDT Disk	ESBDT Mechanical-chemical

Table 3. Two example management action portfolios for the 14 managed impoundments at Mattamuskeet National Wildlife Refuge, North Carolina.—Continued

[Hydroperiod abbreviations are defined in table 2]

Impoundment	Hectares	Non-breeding waterfowl portfolio example	Migrating shorebird portfolio example
MI-10S	62.1	LSBDT Disk	LSBDT Disk
MI-10N	99.7	ESDT No action	ESDT No action
MI-11	183.3	SEMI Mechanical-chemical	SEMI No action

Predictive Models

Waterfowl- and shorebird-use days are the criteria used to evaluate the benefits of each management action portfolio. The total benefit of a portfolio depends on the sum of waterfowl- and shorebird-use days in all impoundments. As a result, critical information needs are the expected numbers of waterfowl- and shorebird-use days provided by each impoundment when it is subject to a specific combination of hydroperiod and vegetation manipulation. Empirical data on bird-use days in response to each of the 16 management actions in each of the 14 impoundments were not available. Therefore, expert elicitation procedures were used to build predictive models and calculate expected bird-use days for the management actions of interest (see table 2).

In the expert elicitation to build predictive models, we relied on the expert judgment of one of the authors, J.D. Stanton (referred to as the “expert” or “subject matter expert”) because he has extensive knowledge of the impoundments at MNWR. The expert was the refuge biologist at MNWR from 1994 through 2002, and in this capacity, he developed annual habitat management plans for the refuge’s impoundments. The expert is familiar with the refuge’s decision-making process, as well as the ecological dynamics of the impoundments, and despite departing from the refuge in 2002, he continues to advise MNWR staff regarding annual management plans for the impoundments.

Working with the subject matter expert, the first step was to create an influence diagram to capture primary ecological relations in a conceptual model (for example, bird responses to habitat conditions and habitat responses to management actions). The influence diagram documents our understanding of ecological drivers and shows connections between available management actions (inputs) and management objectives (outcomes). Influence diagrams per se do not allow quantitative predictions of the objectives, however. Therefore, the next step was to convert the diagram to a Bayesian Belief Network (BBN) model and use additional expert elicitation procedures to parameterize the BBN. The BBN allowed for the prediction of the expected number of bird-use days in response to each management action. The influence diagram and BBN model are described in the next two sections.

Influence Diagram

Water-level and vegetation manipulations have been experimentally linked to waterbird species richness and abundance through changes in food abundance, habitat cover, composition, and structure (for example, Murkin and others, 1997). The expert provided an impoundment-scale influence diagram that explicitly represents causal ecological links (that is, habitat nodes) between management actions and waterbird response in terms of waterfowl- and shorebird-use days (fig. 6).

Invertebrates are an important food source for non-breeding shorebirds, and many studies have demonstrated a positive link between the density of invertebrate prey and shorebird abundance at multiple spatial scales (Goss-Custard, 1970; Colwell and Landrum, 1993). Morphological and behavioral characteristics of shorebirds (for example, tarsometatarsus length) are suited to exploiting invertebrate resources on mudflats and in shallow water areas; small and medium-sized shorebirds, such as those found at MNWR, use areas with less than or equal to 5 centimeters (cm) of water (Ma and others, 2010). Therefore, the influence diagram connects hydroperiod and vegetation manipulations to shorebird-use days through the percent cover of shallow water (<5 cm) and mudflat habitat.

Populations of *Anas Linnaeus* (dabbling duck) may be food limited during the non-breeding season (Baldassarre and Bolen, 2006); most dabbling ducks present at MNWR are dependent on plant food resources during the non-breeding season. In addition, waterfowl species richness and abundance is positively related to the interspersion, or inter-mixing, of emergent vegetation and water (appendix 2; Murkin and others, 1997; Smith and others, 2004). For non-breeding waterfowl, well-interspersed habitats may offer greater food resources or opportunities for seclusion during pair formation (Murkin and others, 1997; Smith and others, 2004). Therefore, the habitat nodes, which represent ecological linkages between management actions and waterfowl abundance, include (1) an

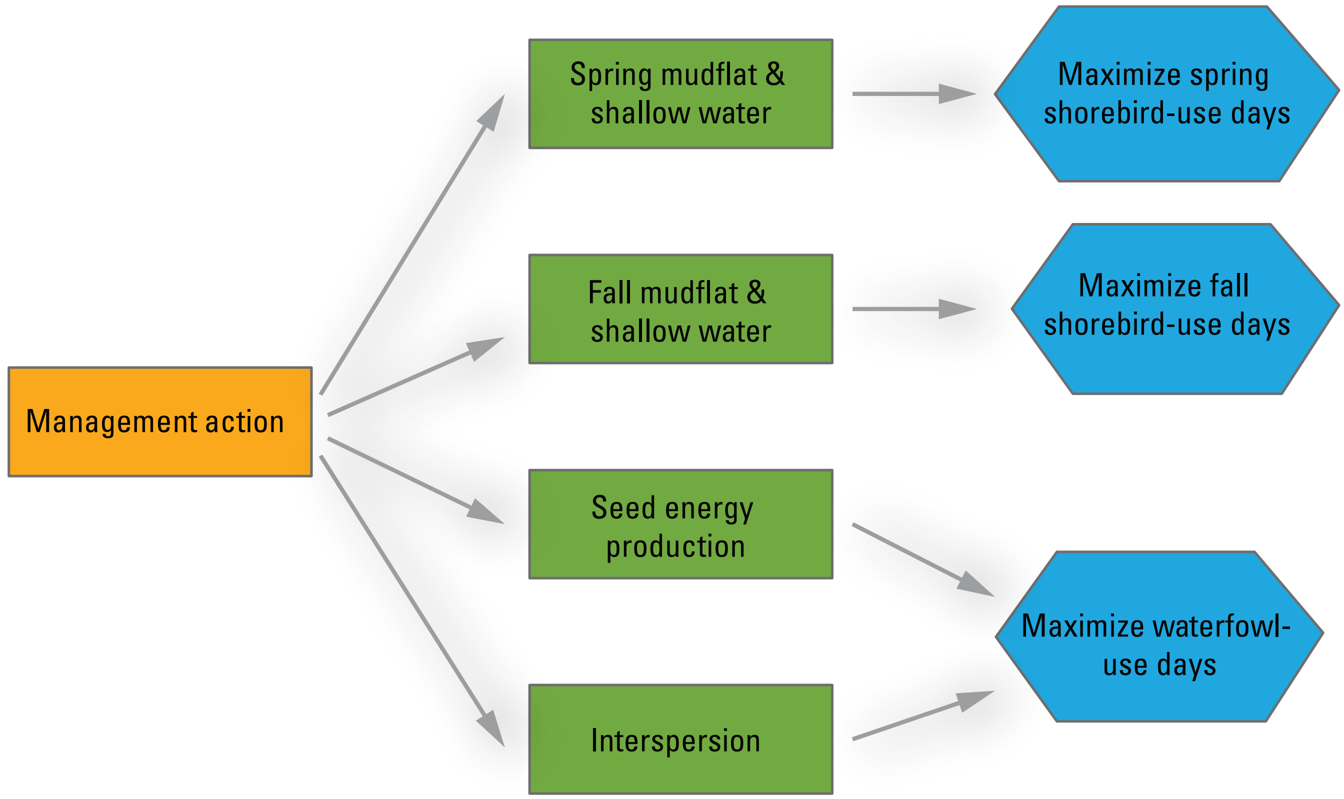

Figure 6. Influence diagram illustrating ecological linkages between hydroperiod and vegetation manipulations, and waterfowl- and shorebird-use days. Relations apply to a single impoundment during the non-breeding season for waterfowl and during fall and spring migrations for shorebirds. (Orange, management action node; green, habitat nodes, that is "ecological links"; blue, management objective nodes)

index to seed energy production and (2) the interspersion of emergent vegetation and water (appendix 2). The seed energy production index used is an extension of that from Naylor and others (2005) and reflects the relative potential of an impoundment to provide energy to nonbreeding dabbling ducks through plant seeds (see detailed methods in appendix 2).

Bayesian Belief Network

To quantitatively predict waterfowl- and shorebird-use days, the influence diagram was converted into a BBN (fig. 7), following practices outlined in Marcot and others (2006). The BBN was developed for a single impoundment, MI-9, at MNWR. MI-9 was chosen because this impoundment afforded relatively frequent opportunities for the subject matter expert to observe waterfowl and shorebird responses to diverse management actions.

We acknowledge that the magnitude of waterfowl- or shorebird-use days resulting from a given management action differs across impoundments at the refuge. For this study, it was assumed that the magnitude of response depends on impoundment size and BBN predictions for MI-9 scaled for other impoundments at MNWR on the basis of their respective sizes. To determine the benefit of a management portfolio (table 3) for fall or spring shorebirds or waterfowl, predicted bird-use days for individual impoundments need to be summed.

Conversion of the influence diagram into a BBN involved two steps.

1. Convert each node of the influence diagram to a BBN node defined by a discrete set of states.

2. Use expert judgment to define conditional probability tables representing causal linkages between nodes.

The Management Action node was converted into a node containing 16 states defined by the 16 management actions listed in table 2. The discrete states for the Habitat and Management Objective nodes are defined and justified in table 4. Further explanation and justification of discrete states is given in appendixes 2 and 3.

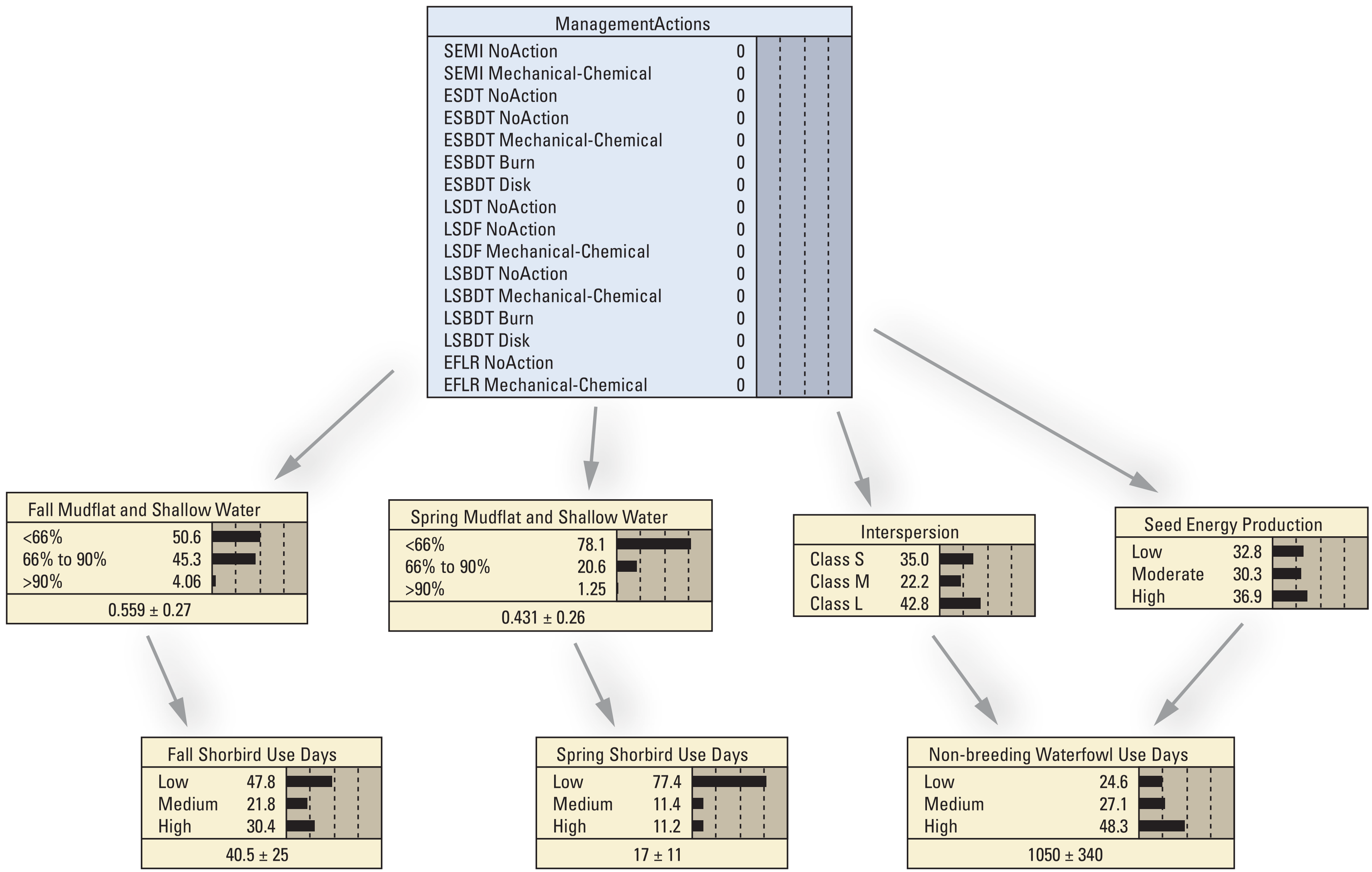

Figure 7. Bayesian Belief Network illustrating ecological linkages between hydroperiod and vegetation manipulations and waterfowl- and shorebird-use days. Relations apply to impoundment MI-9 during the non-breeding season for waterfowl and during fall and spring migrations for shorebirds. Note that conditions shown are averaged across all uncertainty in the model. Use-day predictions are in thousands. (Top node represents management actions; middle nodes, habitat conditions, that is, “ecological links”; bottom nodes, management objectives). [Management actions include hydroperiod abbreviations defined in table 2]

Table 4. Discrete states used to convert the influence diagram (fig. 6) into a Bayesian Belief Network (fig. 7).

[See figure 6 for the influence diagram and figure 7 for the Bayesian Belief Network. Bold italic font indicates nodes. <, less than; >, greater than; %, percent; cm, centimeter]

States	Definitions	Justifications
	Fall/Spring mudflat and shallow water	
<66%	Less than 66% of the impoundment is covered by mudflat and (or) shallow water (<5 cm)	Shorebird management provides <66% open, muddy, or shallow water cover in managed impoundment (Helmers, 1992; Vickery and others, 1996)
66 to 90%	66 to 90 percent of the impoundment is covered by mudflat and (or) shallow water (<5 cm)	Shorebird management provides 66–90% open, muddy, or shallow water cover in managed impoundment (Helmers, 1992; Vickery and others, 1996)
>90%	Greater than 90% of the impoundment is covered by mudflat and (or) shallow water (<5 cm)	Isola and others (2000) provides evidence that some shorebirds prefer to forage in areas with >90% open, shallow water cover
	Seed energy production index	
Low	Emergent plant community receives seed energy production index value less than 15	Expert belief indicates minimal food value for nonbreeding waterfowl (appendix 2)
Moderate	Emergent plant community receives seed energy production index value ranging from 15 to 30	Expert belief indicates moderate food value for nonbreeding waterfowl (appendix 2)
High	Emergent plant community receives seed energy production index value greater than 30	Expert belief indicates high food value for nonbreeding waterfowl (appendix 2)
	Interspersion	
S	The impoundment includes small, disconnected patches of water/bare ground	High level of interspersion beneficial for waterfowl
M	Impoundment contains discernible regions of interspersion states L and S	Moderate response expected by waterfowl
L	Impoundment includes large and connected patches of water/bare ground	Low level of interspersion not preferred by waterfowl
	Fall shorebird-use days	
Low	19,000 shorebird-use days provided by impoundment MI-9 between July 15 and November 15	The expert would be fully satisfied with 76,000 use days. The value chosen for the low state (19,000) represents one-quarter of full satisfaction (appendix 3)
Moderate	38,000 shorebird-use days provided by impoundment MI-9 between July 15 and November 15	The expert would be fully satisfied with 76,000 use days. The value chosen for the moderate state (38,000) represents one-half of full satisfaction (appendix 3)
High	76,000 shorebird-use days provided by impoundment MI-9 between July 15 and November 15	The expert would be fully satisfied with 76,000 use days (appendix 3)
	Spring shorebird-use days	
Low	11,700 shorebird-use days provided by impoundment MI-9 between March 15 and June 1	The expert would be fully satisfied with 46,800 use days. The value chosen for the low state (11,700) represents one-quarter of full satisfaction (appendix 3)
Moderate	23,400 shorebird-use days provided by impoundment MI-9 between March 15 and June 1	The expert would be fully satisfied with 46,800 use days. The value chosen for the moderate state (23,400) represents one-half of full satisfaction (appendix 3)

Table 4. Discrete states used to convert the influence diagram (fig. 6) into a Bayesian Belief Network (fig. 7).—Continued

[See figure 6 for the influence diagram and figure 7 for the Bayesian Belief Network. Bold italic font indicates nodes. <, less than; >, greater than; %, percent; cm, centimeter]

States	Definitions	Justifications
High	46,800 shorebird-use days provided by impoundment MI-9 between March 15 and June 1	The expert would be fully satisfied with 46,800 use days (appendix 3)
	Non-breeding waterfowl-use days	
Low	539,600 waterfowl-use days provided by impoundment MI-9 between September 15 and March 15	On the basis of observed waterfowl-use days, 539,600 waterfowl-use days identifies the 30th percentile for MI-9 (appendix 3)
Moderate	941,600 waterfowl-use days provided by impoundment MI-9 between September 15 and March 15	On the basis of observed waterfowl-use days, 941,600 waterfowl-use days identifies the 70th percentile for MI-9 (appendix 3)
High	1,371,200 waterfowl-use days provided by impoundment MI-9 between September 15 and March 15	On the basis of observed waterfowl-use days, 1,371,200 waterfowl-use days identifies the 95th percentile for MI-9. The refuge biologist would be fully satisfied at this level of waterfowl-use days (appendix 3)

Each node in the BBN (fig. 7) relies on a conditional probability table to define causal linkages between nodes. Through these probability tables, management actions are directly, probabilistically linked to habitat states, and habitat states are directly, probabilistically linked to management objective states. Conditional probability tables were elicited from the subject matter expert. Appendix 4 provides details of the expert elicitation process and contains all conditional probability tables for the nodes in the BBN model of impoundment MI-9. Table 5 is an example of the conditional probability table constructed for the extent of spring mudflat and shallow water habitat; the table shows the likelihood of mudflat and shallow water habitat, given each of the 16 management actions from table 2.

With nodes and conditional probability tables defined, the BBN was implemented in the program Netica® (version 5.15, Norsys Systems Corp., Vancouver, British Columbia). Following implementation, the expert reviewed the behavior of the BBN, examining the response of habitat and management objective nodes to changes in the state of the management action node. This review led to a revision of estimates in a conditional probability table (appendix 4). On the basis of the revised BBN model, table 6 provides expected fall shorebird-, spring shorebird-, and nonbreeding waterfowl-use days for each management action implemented in MI-9. Appendix 5 provides bird-use day estimates for all impoundments at MNWR.

To date, the BBN is fully specified and compiled, and its behavior is adjusted to meet the expectations of the expert. At this stage, Marcot and others (2006) considered “alpha-level” development to be complete and the model ready for internal use and review only. Marcot and others (2006) outline two additional stages of model development, beta and gamma. Beta-level development involves peer review of the model by external subject matter experts and response of the expert to peer feedback, including model revisions when appropriate. The BBN framework has been presented to, and received approval from, management staff at MNWR; it was also evaluated by two peer reviewers. Despite these reviews and revisions by the subject matter expert, we consider our prototype to be “alpha-level,” and we plan to seek additional review by external subject matter experts. With respect to gamma-level development, Marcot and others (2006) emphasize the use of field data to test and update the BBN to increase confidence in its reliability and accuracy, and to test competing hypotheses. The BBN will be tested against monitoring data collected at MNWR using protocols of the Integrated Waterbird Management and Monitoring (IWMM) program (Loges and others, 2014).

For approximately two decades, MNWR has relied on the subject matter expert to use an implicit model to make annual recommendations regarding impoundment management. While acknowledging the need for additional BBN development, we view the alpha-level BBN as an important step forward because it not only provides explicit, testable hypotheses regarding management effects on habitat conditions and abundance of waterfowl and shorebirds, but also increases transparency and defensibility. This model sets the stage for future improvements in the decision-making process as the model is reviewed and revised on the basis of expert feedback and tested and updated using data from ongoing IWMM monitoring.

Table 5. Conditional probability table for extent of mudflat and shallow water in Mattamuskeet National Wildlife Refuge, North Carolina, in spring with hydroperiod and vegetation manipulation.

[Probabilities are based on expert judgment and sum to unity in each row. Hydroperiod abbreviations are defined in table 2. %, percent; <, less than; >, greater than]

Hydroperiod	Vegetation manipulation	Extent of mudflat and shallow water in spring (% cover)		
		<66%	66 to 90%	>90%
SEMI	No action	0.95	0.05	0
	Mechanical-chemical	0.95	0.95	0
ESDT	No action	0.5	0.45	0.05
ESBDT	No action	0.85	0.15	0
	Mechanical-chemical	0.8	0.2	0
	Burn	0.7	0.25	0.05
	Disk	0.6	0.3	0.1
LSDT	No action	0.95	0.05	0
LSDF	No action	0.95	0.05	0
	Mechanical-chemical	0.95	0.05	0
LSBDT	No action	0.95	0.05	0
	Mechanical-chemical	0.95	0.05	0
	Burn	0.95	0.05	0
	Disk	0.95	0.05	0
EFLR	No action	0.25	0.75	0
	Mechanical-chemical	0.25	0.75	0

Tradeoffs Using Portfolio Analysis

To demonstrate the integration of the BBN into MNWR's decision-making process, potential management action portfolios were evaluated using predictions from the BBN. For each portfolio, the predicted bird-use days were summed across all impoundments for each of the three objectives, fall and spring shorebird- and nonbreeding waterfowl-use days:

$$x_{ij} = \sum_{k=1}^{14} x_{ijk} \qquad (1)$$

where

x_{ij} is the number of predicted bird-use days for objective j of portfolio i and

x_{ijk} represents predicted bird-use days for objective j of portfolio i for impoundment k.

In the multi-objective decision analysis, it is necessary to make tradeoffs among the three objectives. To evaluate the performance of each management action portfolio, it is necessary to combine the three objectives into a single index of performance for the portfolio. Here the measurement units for all three objectives are bird-use days, so the simple average of the three bird-use day outcomes for a given portfolio may seem like a reasonable index to the performance of the portfolio. A simple average, however, does not account for the disparity in the ranges of possible outcomes for each of the objectives. For any given management action, predicted use days for waterfowl are an order of magnitude greater than predicted use days for shorebirds, and variability in predicted use days among actions was generally greater for waterfowl than shorebirds (table 6). Therefore, an evaluation of portfolios on the basis of the average of waterfowl- and shorebird-use days would tend to select a portfolio with actions that favored waterfowl

Table 6. Predicted use days for impoundment MI-9, Mattamuskeet National Wildlife Refuge, North Carolina, and 16 combinations of hydroperiod and vegetation manipulation.

[Predictions were made using the Bayesian Belief Network model (see figure 7), parameterized with expert judgment. Hydroperiod abbreviations are defined in table 2]

Hydroperiod	Vegetation manipulation	Predicted use days (in thousands)		
		Fall shorebird	Spring shorebird	Non-breeding waterfowl
SEMI	No action	23.7	13.3	912
	Mechanical-chemical	25.6	13.3	888
ESDT	No action	33	23.1	1,080
ESBDT	No action	27.4	15.4	1,050
	Mechanical-chemical	37.5	16.5	972
	Burn	41.7	18.9	1,050
	Disk	45.8	21.2	1,160
LSDT	No action	40.4	13.3	1,090
LSDF	No action	42.2	13.3	1,130
	Mechanical-chemical	48.6	13.3	1,050
LSBDT	No action	40.4	13.3	1,080
	Mechanical-chemical	44.1	13.3	976
	Burn	45.9	13.3	1,040
	Disk	47.8	13.3	1,180
EFLR	No action	50.1	28.1	1,080
	Mechanical-chemical	53.8	28.1	1,050

in a way that may not be intended; this approach ignores the fact that a given absolute change in predicted use days might be valued differently by a refuge biologist, depending on the objective. As an example, the consequences of switching from ESBDT to ESBDT with mechanical-chemical manipulation are examined. In absolute terms for MI-9, this change results in an additional 10,100 use days for fall shorebirds (+37%), an additional 1,100 use days for spring shorebirds (+7%), and a loss of 78,000 use days for non-breeding waterfowl (-8%) (table 6). There is a clear net loss of use days, but a biologist might select ESBDT with mechanical-chemical manipulation when placing more value on a 37 percent increase in fall shorebird-use days than an 8 percent loss of waterfowl-use days. The solution to this problem is to use weights for the objectives.

The subject matter expert acting as a proxy decision maker indicated that weights should be based on the relative importance of MNWR to the viability of flyway-scale shorebird and waterfowl populations. Data are not available to enable an evaluation of the importance of MNWR to flyway populations, although IWMM has developed an energy-based migration model that might provide these insights in the future (Lonsdorf and others, 2016). Given that it was not possible to determine weights in the way that the decision maker would prefer, it was decided to (1) use a set of placeholder weights as a base-case scenario for the decision analysis and (2) explore the sensitivity of the solutions to the objective weights (and costs) used as a base-case scenario. The following were used as placeholder weights: waterfowl-use days = 0.5, fall shorebird-use days = 0.3, and spring shorebird-use days = 0.2. Objective weights solve the problem associated with the variety of ranges associated with each of the objectives; weights ensure that the desired amount of importance is placed on the incremental changes in outcomes that result from management actions. The placeholder weights used here emphasize waterfowl because MNWR (1) was established to benefit wintering waterfowl, (2) is recognized as the most important habitat for wintering waterfowl in North Carolina, and (3) traditionally manages for non-breeding waterfowl. Clearly, there is subjectivity to determining the weights, and different decision makers might have different weights for these objectives. Again, following the decision analysis with this set of weights, sensitivity analysis was used to determine the implications of alternative weights for the solutions in the base-case scenario.

The weighted average of bird-use days is an improvement over using a simple average as an index to portfolio performance, but it does not account for the decision maker's satisfaction with a particular outcome and attitude toward risk when making this decision. To accurately capture the decision maker's level of satisfaction and provide flexibility to incorporate attitudes toward risk, a "utility function" was used to transform predicted bird-use days to a utility expressed as a measure of satisfaction ranging from 0 (unsatisfied) to 1 (complete satisfaction). Bird-use day predictions were normalized using a general formal:

$$U_{ij} = \frac{x_{ij} - Min_j}{Max_j - Min_j} \tag{2}$$

where

- U_{ij} is the normalized score for objective j of portfolio i,
- Min_j is the minimum predicted bird-use days across all portfolios, and
- Max_j is the maximum predicted bird-use days across all portfolios.

Minimum and maximum predicted bird-use days for each objective are presented in table 7. For a portfolio i, a weighted average utility score was calculated using

$$U_i = \sum_{j=1}^{3} w_j U_{ij} \tag{3}$$

where

- U_i is the utility score of portfolio i, and
- w_j is the weight assigned to objective j (table 8).

U_i was our measure of "fitness" for evaluating portfolios with the genetic algorithm (Appendix 6).

Table 7. Minimum and maximum predicted bird-use days for fall- and spring-migrating shorebirds and non-breeding waterfowl at Mattamuskeet National Wildlife Refuge, North Carolina.

[These values were used to convert predicted bird-use days for portfolios of management actions into normalized scores (see equation 2)]

	Fall shorebird	Spring shorebird	Non-breeding waterfowl
Minimum bird-use days	204,395	114,703	7,658,358
Maximum bird-use days	463,986	242,342	10,176,647

The cost of a portfolio cannot exceed the total funds available. Details of cost calculations for hydroperiod and vegetation manipulations, and costs of management actions for all impoundments, are presented in appendix 7. For illustration purposes, table 2 reports costs for actions implemented at impoundment MI-9. Total expense of a portfolio is defined as the sum of costs assigned to its constituent management actions. On the basis of feedback from the subject matter expert, it was assumed that $40,000 represents a typical budget for impoundment management at MNWR, and this budget was used for the base-case scenario. The effect of halving or doubling this budget on the portfolio analysis was evaluated using sensitivity analysis.

Evaluating tradeoffs among alternative portfolios presents a computational challenge. With 16 management actions and 14 impoundments, the number of decision variables in a constrained optimization (for example, integer programming) is equal to 224 (16 actions × 14 impoundments), which is beyond the capability of commonly used spreadsheet applications for constrained optimization (Microsoft Solver). Therefore, a heuristic genetic algorithm (Scrucca, 2013; R Core Team, 2015) was used for the evaluation of the portfolios (appendix 7). This heuristic approach may not locate the optimum solution among all alternatives, but it presents fewer computational hurdles and thus is more practical than other approaches, for example, integer programming (Chinneck, 2015). The genetic algorithm was expected to locate a portfolio with a relatively high weighted average utility score while also respecting budgetary constraints.

Base-Case Scenario

The preferred portfolio under the base-case scenario includes the ESBDT hydroperiod (fig. 3) with disking for 11 of 14 impoundments (Portfolio 1; table 8). Relative to other management actions, ESBDT with disking provides nearly the best possible predicted bird-use days for waterfowl (2d best action out of 16; appendix 5) and good outcomes for fall (6th best) and spring (4th best) shorebirds at a reasonable expense (7th least expensive action; appendix 7). At a budget less than $40,000, Portfolio 1 resulted in more than 376,000 fall shorebird-use days, more than 182,000 spring shorebird-use days, and nearly 10 million non-breeding waterfowl-use days (table 8).

The implementation of ESBDT with disking in MI-5 and MI-7 would have resulted in an overall portfolio cost ($40,250) that exceeded the budget constraint of $40,000. Instead, the management action assigned to these impoundments was LSBDT (fig. 4) with disking. At a lower financial cost (6th best), this action improved outcomes for fall shorebirds (4th best) and non-breeding waterfowl (1st) while being tied for the fewest spring shorebird-use days among potential actions. This tradeoff among the three objectives aligns with the greater weight given to bird-use days for fall shorebirds and non-breeding waterfowl.

Table 8. Selected portfolios of management actions for Mattamuskeet National Wildlife Refuge, North Carolina, impoundments given different objective weights and budgets.

[Portfolios were selected through the application of a genetic algorithm. Weights are presented for fall shorebirds (FS), spring shorebirds (SS), and non-breeding waterfowl (WF). For each portfolio, the total number of predicted use days (BUDS) for the three bird objectives and the associated cost are reported. Hydroperiod abbreviations are defined in table 2]

FS Weight	0.3	0.1	0.2	0.3	0.3
SS Weight	0.2	0.0	0.1	0.2	0.2
WF Weight	0.5	0.9	0.7	0.5	0.5
Budget	$40,000	$40,000	$40,000	$20,000	$80,000
Wetland	**Portfolio 1**	**Portfolio 2**	**Portfolio 3**	**Portfolio 4**	**Portfolio 5**
MI-1	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-2W	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-2E	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-3	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-4	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESBDT, Disk	ESBDT, Disk
MI-5	LSBDT, Disk	LSBDT, Disk	LSBDT, Disk	LSDT, No action	ESBDT, Disk
MI-6	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	LSDT, No action	ESBDT, Disk
MI-8W	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-8E	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-9	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESBDT, Disk	ESBDT, Disk
MI-10S	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESBDT, Disk	ESBDT, Disk
MI-10N	ESBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESDT, No action	ESBDT, Disk
MI-7	LSBDT, Disk	LSBDT, Disk	LSBDT, Disk	LSBDT, Disk	ESBDT, Disk
MI-11	ESDT, No action	LSDT, No action	LSDT, No action	ESDT, No action	EFLR, No action
FS BUDS	376,323	401,040	401,040	328,820	401,500
SS BUDS	182,925	114,703	114,703	188,093	193,279
WF BUDS	9,890,124	10,040,420	10,040,420	9,578,687	9,883,072
Cost	$39,830	$37,380	$37,380	$19,997	$53,148

The subject matter expert indicated that disking was not possible in MI-11, so disking actions were excluded from this impoundment by setting their costs prohibitively high (appendix 7). Rather than ESBDT with disking, the action assigned to MI-11 was ESDT (fig. 3) with no action on vegetation manipulation. Of the 14 non-disking actions, selection of ESDT may have been driven mostly by cost considerations. Only one impoundment (MI-4) is larger than MI-11, and because of its size, 9 of 14 potential management actions for MI-11 required greater than 30 percent of the $40,000 budget. ESDT with no action on vegetation manipulation was inexpensive (3rd) while providing good outcomes for bird-use days of spring shorebirds (3rd) and waterfowl (tied for 5th) and a moderate outcome for fall shorebird-use days (13th).

Sensitivity Analysis

A sensitivity analysis was performed to identify preferred solutions under a variety of scenarios for objective weights and budgetary constraints. Portfolios 2 and 3 in table 8 represent the alternative weight schemes defined by the expert acting as a proxy decision maker.

Again, each scheme emphasizes waterfowl because MNWR (1) was established to benefit wintering waterfowl, (2) is recognized as the most important habitat for wintering waterfowl in North Carolina, and (3) traditionally manages for non-breeding waterfowl. In addition to different weights, the implications of halving or doubling of the budget was explored (Portfolios 4 and 5; table 8).

The selected portfolio differed depending on the objective weights and the budget specified. With an increased emphasis on the non-breeding waterfowl objective, the assigned action for 13 of 14 impoundments included a LSBDT hydroperiod with disking (Portfolios 2 and 3; table 8). At a reasonable cost (6th), this action provided the best waterfowl-use days (1st), a good outcome for fall shorebirds (4th), and tied for fewest spring shorebird-use days. With disking actions precluded (see “Base-Case Scenario” section), the action implemented in MI-11 in Portfolios 2 and 3 included a LSDT (fig. 4) hydroperiod with no action on vegetation manipulation. This combination provided a good bird-use day outcome for waterfowl (4th), a moderate outcome for fall shorebirds (tied for 10th), and tied for fewest spring shorebird-use days. This action also minimized the cost (tied for 1st) of treating MI-11, the second largest impoundment. Overall, Portfolios 2 and 3 each provided more than 401,000 fall shorebird-use days, greater than 114,000 spring shorebird-use days, and more than 10 million waterfowl-use days at a cost of about $37,000 (table 8).

Relative to the base-case scenario (Portfolio 1; table 8), cutting the budget in half shifted seven impoundments from ESBDT with disking actions to ESDT with no action on vegetation manipulations (Portfolio 4; table 8). ESDT with no vegetation manipulation is a cheaper treatment that improves spring shorebird-use days (3rd), reduces waterfowl-use days (tied for 5th), and reduces fall shorebird-use days (13th). The other alteration to the portfolio was the assignment of LSDT hydroperiod with no action on vegetation manipulation to two impoundments; this action was absent from the portfolio with a budget of $40,000. LSDT with no vegetation manipulation tied for cheapest action, and it provided a good outcome for waterfowl-use days (4th), moderate fall shorebird-use days (tied for 10th), and a poor outcome (tied for last) for spring shorebirds. At just under $20,000, Portfolio 4 provided greater than 328,000 fall shorebird-use days, approximately 188,000 spring shorebird-use days, and more than 9.5 million waterfowl-use days.

Doubling the budget for Portfolio 5 (table 8) produced three changes relative to Portfolio 1, the result of the base-case scenario. Actions for MI-5 and MI-7 went from LSBDT with disking to ESBDT with disking. Tradeoffs between these management actions were discussed in full earlier (see “Base-Case Scenario” section). Essentially, ESBDT with disking provided a more balanced outcome across our three objectives but was more expensive. A doubling of the budget provided the opportunity to implement this action in MI-5 and MI-7. The management action for MI-11 changed from ESDT with no vegetation manipulation to the EFLR hydroperiod (fig. 5) with no action on vegetation manipulation. The latter action provided improved bird-use days for fall (2d) and spring (tied for 1st) shorebirds and provided a good outcome for waterfowl (tied for 5th). Aside from these three changes, the management action for all other impoundments remained as the ESBDT hydroperiod with disking. The majority of actions remained unchanged despite the fact that the total cost for Portfolio 5 was approximately $53,000, a value far short of the $80,000 budget constraint. These results indicate that doubling the budget may not substantially affect management planning for most impoundments at MNWR. Portfolio 5 provided more than 400,000 fall shorebird-use days, more than 193,000 spring shorebird-use days, and approximately 9.8 million waterfowl-use days.

Future Changes to the Decision Framework

The need to balance multiple waterbird objectives, that is, non-breeding waterfowl and migrating shorebirds, across a collection of impoundments challenges annual management planning efforts at MNWR. In this study, structured decision-making principles and practices were used to individually address and integrate components of MNWR’s annual decision. The study (1) clearly defined the decision problem, (2) explicitly captured the refuge’s waterbird objectives, (3) identified alternative management portfolios, (4) developed and applied an expert-based model to evaluate outcomes of alternative portfolios relative to waterbird objectives, and (5) provided preferred portfolios of management actions, assuming different weights for waterbird objectives and budgetary constraints. The decision framework offers a foundation for rigorous, transparent, and defensible decisions regarding the collective annual management of MNWR's impoundments.

The development of a decision framework is an iterative process, and each component of the framework is open to revision and further development. To date (2016), the framework has been presented to MNWR's Refuge Manager, Deputy Refuge Manager, and Refuge Biologist, and they have incorporated it into their decision-making process. In the future, the framework may be revisited and revised on the basis of the needs of the refuge and lessons learned during implementation (for example, additional objectives, unanticipated constraints, new management actions).

The difficulty of managing impoundments at MNWR is increased by uncertainties about effects of management actions on habitat and the responses of waterfowl and shorebirds to habitat conditions. In the predictive BBN model, these parametric uncertainties were accounted for through conditional probability tables linking management actions to habitat states and habitat states to predicted use days. Probabilities in these tables were elicited from the subject matter expert following best practices for expert elicitation (appendix 4; Gregory and others, 2012). Nevertheless, there is a degree of subjectivity in the current probabilities in that they depend on the expert's interpretation of his experiences and observations while associated with MNWR. To update these probabilities, we ensured that all nodes in the BBN were monitored by the IWMM (Loges and others, 2014) or were derived from IWMM monitoring data. As a consequence, ongoing IWMM monitoring at MNWR can be used to update the conditional probability tables, and, over time, the probabilities increasingly will be based on empirical data and less on the expert-elicited values.

Empirical updating of the conditional probability tables is accommodated by the Netica® software used to create the BBN model. Specifically, IWMM monitoring data can be provided to the software as case files. Each case file will contain cases indicating states for management action (for example, semi-permanent hydroperiod), spring mudflat and shallow water (for example, < 66%), fall mudflat and shallow water (for example, >90%), interspersion (for example, S), seed energy production index (for example, high), spring shorebird-use days (for example, high), fall shorebird-use days (for example, medium), and waterfowl-use days (for example, low). Although the BBN was developed for MI-9, observations from other impoundments could be used as cases if use day observations were rescaled to MI-9 on a per hectare basis. Therefore, as many as 14 cases could be used to update the BBN on an annual basis. As understanding of the system improves over time, we anticipate improved management outcomes.

Another type of uncertainty with the potential to affect management of MNWR's impoundments relates to competing models (Williams, 1997, 2001). In the current framework, a single model was used representing linkages among management actions, habitat states, and bird use. Future development of this framework reasonably would include review by subject matter experts (beta-level development; Marcot and others, 2006) who might identify competing models. For example, one potential competing model might include an additional ecological-link node for shorebirds that reflects the abundance of aquatic invertebrates, an important food resource (Goss-Custard, 1970; Colwell and Landrum, 1993). Competing models could be weighted to reflect the respective degrees of confidence on the basis of expert opinion, empirical observations, or a combination of the two. Weighted predictions from competing models can be used to inform the selection of alternative portfolios. Assuming competing models use parameters linked to ongoing monitoring, model weights can be updated over time, resulting in improved management decisions.

This discussion dealt with ways to incorporate and address parametric and competing model uncertainties, collectively referred to as "structural uncertainties" (Williams, 1997, 2001). Other recognized types of uncertainties include partial management control (deviations from intended management actions, for example, owing to mechanical pump failures), environmental variation (for example, occurrence of hurricane), and partial observability (for example, owing to sampling waterbird use throughout the season) (Williams, 1997, 2001). The BBN from this study could be extended to incorporate partial management control and environmental variation through additional nodes. For example, a node representing mechanical pump function or failure could be inserted between the management action and habitat nodes. Two sets of conditional probability tables linking management actions to habitat conditions could be developed, one representing pump function and one pump failure, and bird-use day predictions could be made that account for the chance occurrence of equipment failure. The IWMM is working to characterize and quantify partial observability uncertainties resulting from its current monitoring protocols, and it is anticipated that future revisions of the protocols will reduce these uncertainties.

Ensuring adequate habitat for migratory waterbirds requires cooperation and coordination across refuges and other public and private lands at regional and flyway scales. As a result, land managers and waterbird biologists desire an improved understanding of the manner in which their management actions affect conservation outcomes at regional and flyway scales. The decision framework and modeling approach developed for this case study could be extended to identify portfolios of management actions for impoundments located at multiple refuges and other public and private lands. Such a regional or flyway decision framework would require refuges and other public and private land managers to cooperatively develop each component, including a decision statement, objectives, management alternatives, and a predictive model. The promise of these cooperative relations ultimately may be realized through the IWMM. IWMM has established a goal of providing waterbird management decision support at multiple, integrated spatial scales. Refuge-specific decision frameworks, such as this one for MNWR, represent a first step by the IWMM to actively engage land managers and waterbird biologists to develop decision frameworks. Ongoing discussions within the IWMM focus on the logistics of making such decision support available to land managers and waterbird biologists across multiple flyways. Once these discussions are resolved, there will be abundant opportunities to develop multi-scaled decision frameworks addressing pressing waterbird management decisions.

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Appendixes 1, 2, 3, 4, 5, 6, and 7

Appendix 1

Glossary of Hydroperiod Terms.

Appendix 2

Waterfowl Habitat Modeling.

Appendix 3

Building Predictive Models with Expert Judgment.

Appendix 4

Expert Elicitation of Conditional Probability Tables.

Appendix 5

Bird-Use Day Estimates.

Appendix 6

Genetic Algorithm Approach to Portfolio Analysis.

Appendix 7

Management Action Costs.

Appendix 1. Glossary of Hydroperiod Terms

Full pool: A water level within the impoundment that is typically 10–20 inches deep, and in semi-permanent impoundments 24–36 inches deep, and allows for 1–2 feet of freeboard before the water would overtop the earthen berm of the impoundment.

Ditch top: A water-level reference point indicating when the impoundment is dewatered with the exception of internal ditches, which remain filled to the top.

Below ditch top: A water-level reference point that is 1–3 feet below the capacity of interior ditches.

Drawdown: Draining water from the impoundment using water-control structures (for example, removing stop logs from a flash-board riser or opening a flap gate) or pumping water out of the impoundment using diesel- or electric-powered pumps.

Gradual drawdown: Dewatering an impoundment at a rate of 3–4 inches every 2 weeks.

Flood, flooded, flooding: Pumping or gravity flow of water into an impoundment at a rate of 3–4 inches every few days.

Appendix 2. Waterfowl Habitat Modeling

Seed Energy Production Index

Naylor and others (2005) describe a seed production index (SPI) that positively correlates with masses of seeds produced per hectare across wetlands. Integrated Waterbird Management and Monitoring (IWMM) monitoring protocols capture data needed to calculate SPI (Loges and others, 2014). The use of this metric as an index to food abundance for waterfowl was considered for this study.

To gather input for SPI calculations, Naylor and others (2005) visually assessed seed head size, seed head density, and percent horizontal coverage for each moist-soil plant type in selected wetlands. Seed head size was categorized as small or large on the basis of deviation from an observed average, and seed head density was categorized as low, moderate, or high on the basis of the amount of bare ground and the proportion of seed heads to stems. Naylor and others (2005) assigned plant types to one of five horizontal coverage categories: 1–10 percent, 11–25 percent, 26–50 percent, 51–75 percent, or 76–100 percent.

For SPI calculations, Naylor and others (2005) assigned each plant type a quality score ranging from 1 to 4 on the basis of its combined seed head size and density categories. Plant types with large seed head sizes and higher seed head densities received greater quality scores. Similarly, each plant type received a score ranging from 1 to 5 on the basis of its area category; scores were correlated with area category rank. To calculate a SPI value for a wetland, Naylor and others (2005) multiplied quality and area scores for each plant type and summed the resulting values across all plant types.

The subject matter expert provided waterfowl food plant types, seed head sizes, seed head densities, and areas for common plant communities observed within impoundments at Mattamauskeet National Wildlife Refuge (MNWR). The ranking of these communities on the basis of SPI values was not consistent with the expert's experience regarding the food value of these communities for waterfowl.

To address this inconsistency, the expert identified a need to enhance the SPI to incorporate an index of seed energy content for each plant type. Consequently, we introduced an additional term into the calculations for each plant type. Specifically, for each waterfowl food plant type (i) at MNWR, an Energy Index (EI_i) was calculated using

$$EI_i = \frac{TME_i}{TME_{max}}$$

where

TME_i is the true metabolizable energy of plant type i and

TME_{max} is the maximum true metabolizable energy across all plant types at MNWR.

EI ranges from 0 (no true metabolizable energy) to 1 (maximum possible true metabolizable energy). TME values are from Hoffman and Bookhout (1985), Sherfy (1999), Checkett and others (2002), and Dugger and others (2006). For each plant type, the quality score, area score, and energy index were multiplied, and the resulting values were summed across all plant types to arrive at a Seed Energy Production Index (SEPI) value for an impoundment. SPI values produced from IWMM data could be similarly modified to produce SEPI values using published true metabolizable energy estimates.

Table 2-1 provides values for SPI and SEPI calculations for two past plant communities observed by the expert at MNWR. Rankings of plant communities by SEPI values agreed with the beliefs of the expert about the food value of the communities for waterfowl, so SEPI was adopted for this case study. For the BBN, the expert identified SEPI thresholds by examining calculated SEPI values for multiple communities of low, moderate, or high food value for waterfowl. On the basis of these examinations, the expert considered low food value communities to have a SEPI of less than 15, moderate value communities to have a SEPI of 15–30, and high value communities to have a SEPI of greater than 30. SPI and SEPI calculations are presented in table 2-1.

Table 2-1. Seed Production Index and Seed Energy Production Index calculations for two plant communities observed within impoundments at Mattamuskeet National Wildlife Refuge, North Carolina, by J.D. Stanton, the subject matter expert.

[Seed Production Index value is the sum of QS * AS for each community, whereas Seed Energy Production Index value is the sum of QS * AS * EI for each community. QS, Quality score; AS, Area score; EI, Energy index; kcal/g, kilocalorie per gram; %, percent]

Plant type	Seed head			Area		True metabolizable energy (kcal/g)	Energy Index (EI)	QS * AS	QS * AS * EI
	Size	Density	Quality Score (QS)	Coverage	Area Score (AS)				
Community 1									
Fall panicum	Large	High	4	76–100%	5	2.6	0.93	20	18.6
Foxtail	Small	Moderate	2	11–25%	2	2.8	1	4	4
Barnyard grass	Small	Low	1	1–10%	1	2.6	0.93	1	0.93
						Seed Production Index			25
						Seed Energy Production Index			23.53
Community 2									
Fall panicum	Large	Moderate	3	51–75%	4	2.6	0.93	12	11.16
Smartweed	Large	Moderate	3	1–10%	1	1	0.36	3	1.08
Dwarf spikerush	Small	Low	1	26–50%	3	0.5	0.18	3	0.54
Bidens spp.	Large	High	4	26–50%	3	0.55	0.2	12	2.4
						Seed Production Index			30
						Seed Energy Production Index			15.18

Interspersion

Suir and others (2013) described three configuration classes for water in a landscape. The IWMM has adopted and slightly modified these three classes for monitoring water/bare ground configuration within a wetland. The three IWMM classes and their definitions are

- Class S contains small, disconnected patches of water/bare ground;
- Class M contains discernible regions of classes L and S; and
- Class L includes large and connected patches of water/bare ground features.

These three classes can occur where water/bare ground covers different percentages of wetlands, as illustrated in figure 2-1, but once water/bare ground is greater than 60 percent, the most likely configuration is class L.

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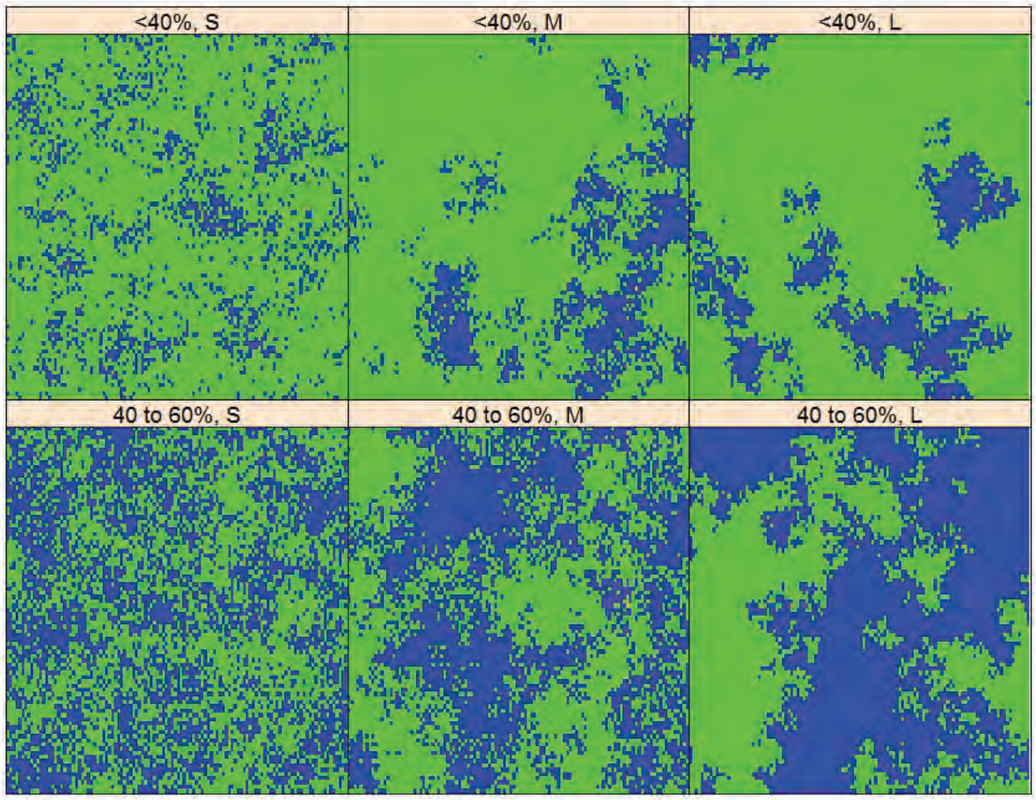

Figure 2-1. Examples of three configuration categories L, S, and M. The three categories are illustrated for different levels of water/bare ground cover: less 40 percent and 40 to 60 percent. Water/bare ground areas are represented in blue; vegetated areas are represented in green. (S, small, disconnected patches of water/bare ground; M, discernable regions of classes L and S; L, large and connected patches of water/bare ground)

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Appendix 3. Building Predictive Models with Expert Judgment

Discrete States for Shorebird-Use Days

Expert-elicitation techniques were used to arrive at discrete shorebird-use day states for fall and spring. This process involved three steps: (1) elicit fall and spring migration curves for impoundment MI-9 under ideal conditions, (2) calculate shorebird-use days from migration curves, and (3) identify shorebird-use days representing different discrete states.

The subject matter expert (coauthor J.D. Stanton) participated in the elicitation process, following the best practices of Gregory and others (2012). As an initial step, the influence diagram was reviewed, and the node definitions were clarified, as well as causal relations between nodes. The authors, including the expert, reviewed the common cognitive biases— anchoring, availability, and overconfidence—which can lead to unreliable expert-based parameter estimates. To guard against cognitive biases, the expert was asked to employ a set of techniques, including (1) maintaining an awareness of the potential for cognitive biases throughout the elicitation process, (2) considering reasons why his estimates might be wrong prior to responding, and (3) preparing to explain the mental model used to provide his estimate, if necessary. Finally, in the interest of considering relevant prior data, the expert was provided with migration curves for *Charadrius semipalmatus* (semi-palmated plover), *Tringa flavipes* (lesser yellowlegs), and *Tringa melanoleuca* (greater yellowlegs), three common shorebird species at Mattamuskeet National Wildlife Refuge (MNWR; personal observation by J.D. Stanton). The migration curves were based on eBird data for North Carolina from 2010 to 2014 (http://www.ebird.org). The exploration of IWMM migration curves was considered, but we found that survey effort was insufficient to allow the full migration curve to be explored. The expert was cautioned against anchoring on eBird data when providing his own migration curves.

In eliciting migration curves, the expert was asked to assume management actions and habitat conditions occurred that would produce the ideal or fully satisfactory number of shorebird-use days for MI-9. With these assumptions as context, the expert created migration curves by answering the following questions:

- When do shorebirds first arrive at MI-9?
- What is (are) the peak count(s) for shorebirds?
- When does (do) the peak count(s) for shorebirds occur?
- When do shorebirds depart MI-9?

The answers to these questions provided data points that enabled the expert to draw out migration curves for fall and spring shorebirds on standard graph paper (fig. 3-1). From these migration curves, we extracted weekly counts for shorebirds and used the trapezoidal rule (Farmer and Durbian, 2006) to determine the area under the migration curve, which is the shorebird-use day estimate. The fall estimate was approximately 76,000 use days, whereas the spring estimate was 46,800. These values defined “high” use discrete states for shorebirds during the fall and spring migrations, respectively. The expert defined two additional use day states, “low” and “moderate” as 25 percent and 50 percent, respectively, of the high use. For fall migration, low corresponded to 19,000 shorebird-use days and moderate to 38,000. For spring, these same states were equal to 11,700 and 23,400 shorebird-use days, respectively. Low, moderate, and high shorebird-use day states were used as reference points in the frequency elicitation to parameterize the Bayesian Belief Network (see appendix 4).

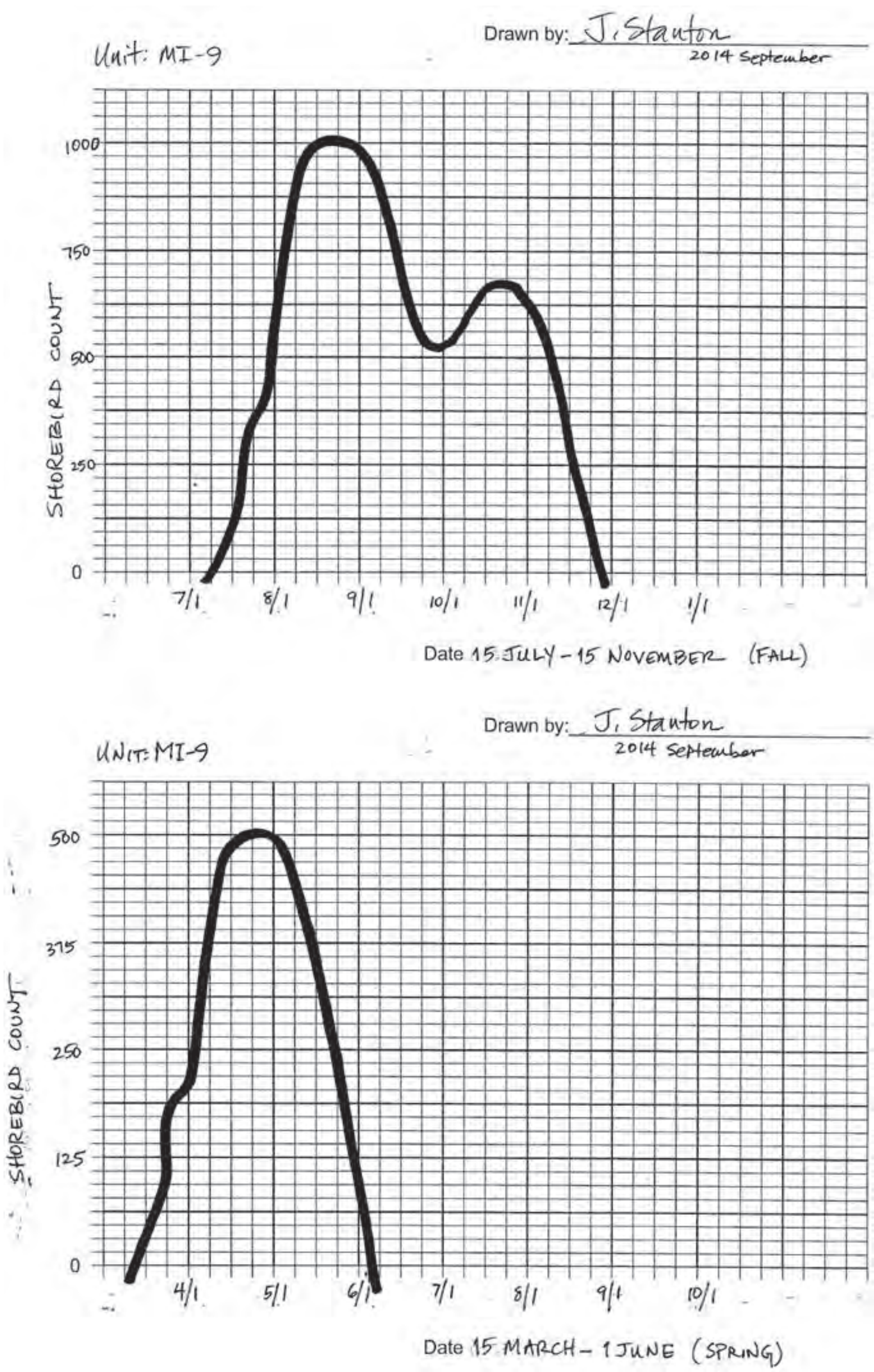

Figure 3-1. Graphs showing fall (top) and spring (bottom) shorebird migration curves produced by subject matter expert J.D. Stanton for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

Discrete States for Waterfowl-Use Days

A normal distribution was used to define discrete states for waterfowl-use days for MI-9. The mean and standard deviation for the normal distribution were based on three consecutive annual estimates of waterfowl-use days calculated using data and functions in the Access database of the Integrated Waterbird Management and Monitoring program (table 3-1).

The percentiles from the normal distribution were presented to facilitate the definition of discrete states by the expert (table 3-2). The following is an example of the explanation of the percentiles to the expert:

“The 25th percentile occurs at approximately 482,000 waterfowl-use days. The meaning of this value can be grasped by

Table 3-1. Waterfowl-use days for three consecutive years at impoundment MI-9, Mattamuskeet National Wildlife Refuge, North Carolina.

[Waterfowl-use day estimates were produced using data and tools in the Integrated Waterbird Management and Monitoring program Access database]

Time period	Waterfowl-use days
Sept. 15, 2010–Mar. 15, 2011	950,040
Sept. 15, 2011–Mar. 15, 2012	298,181.50
Sept. 15, 2012–Mar. 15, 2013	973,683.50
Mean	740,635
Standard deviation	383,358.30

Table 3-2. Percentiles from normal distribution defined using the mean and standard deviation of observed waterfowl-use days for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[See table 3-1 for mean and standard deviation of observed waterfowl-use days]

Percentile	Waterfowl-use days
5th	110,067
10th	249,342
15th	343,310
20th	417,993
25th	482,064
30th	539,602
35th	592,919
40th	643,512
45th	692,462
50th	740,635
55th	788,808
60th	837,758
65th	888,351
70th	941,668
75th	999,206
80th	1,063,277
85th	1,137,960
90th	1,231,928
95th	1,371,203

considering annual waterfowl-use days over a 100-year period at MI-9. Twenty-five years would have waterfowl use less than or equal to 482,000, whereas 75 years would have a value greater than 482,000."

On the basis of these explanations, the expert chose to use the 30th (~539,600 waterfowl-use days), 70th (~941,600), and 95th (~1,371,200) percentiles to define low, moderate, and high waterfowl-use day states, respectively, and to predict waterfowl abundance. Conditional probabilities for these states were elicited (see appendix 4).

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Appendix 4. Expert Elicitation of Conditional Probability Tables

To compile and run the Bayesian Belief Network (BBN), conditional probability tables linking management actions to habitat states, and habitat states to waterfowl and shorebird-use states, were needed. Available empirical data did not enable us to populate conditional probability tables, so the required probabilities were elicited from the subject matter expert, J.D. Stanton, for Mattamuskeet National Wildlife Refuge (MNWR).

We prepared the subject matter expert to participate in the elicitation process following best practices of Gregory and others (2012). The influence diagram on which the BBN is based was reviewed with the expert, and node definitions, as well as causal relations linking nodes, were clarified. Common cognitive biases that can lead to unreliable expert-based parameter estimates, including anchoring, availability, and overconfidence, were reviewed. To guard against cognitive biases, the expert was asked to employ a set of techniques, including (1) maintaining an awareness of the potential for cognitive biases throughout the elicitation process, (2) considering reasons why his estimates might be wrong prior to responding, and (3) preparing to explain, if necessary, the mental model used to provide his estimate. Alternative formats for elicitation questions were also discussed with the expert, and a format that worked best for him was identified. Specifically, we considered directly eliciting probabilities against eliciting the frequency of a particular outcome state over a 20-year period. The expert indicated that it would be easier for him to express responses in terms of frequency over a 20-year period. Partly, his comfort with frequencies stemmed from the fact that his experience with the impoundments at MNWR spans an approximately 20-year period. The following is an example of our elicitation questions:

"Assume that MI-9 possesses less than 66 percent spring mudflat and shallow water every year for 20 years. In how many years will each of the spring shorebird-use day states occur?"

At points during the elicitation process, we purposely discussed, at length if necessary, the mental model used to produce his frequency estimates. This was done when eliciting probabilities linking management actions to habitat states and when eliciting probabilities linking habitat and bird-use states.

The elicited frequencies were converted to probabilities for entry into the BBN in Netica ®. With the initial version of the BBN in place, the subject matter expert reviewed the behavior of the model, and this review led to a revision of estimates in the conditional probability tables. For the seasonal, late drawdown to below ditch top with no vegetation manipulation, the expert increased the probability of obtaining a high seed energy production index value. He made this change because late germinating species, such as wild millet, tend to have denser and more energy rich seed heads than early season plants. Final conditional probability tables incorporated into the BBN are reported in tables 4-1 through 4-7.

Table 4-1. Conditional probability for extent of mudflat and shallow water in fall, conditional on hydroperiod and vegetation manipulation, for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. See table 2 for abbreviation definitions for hydroperiods. <, less than; >, greater than; %, percent]

Hydroperiod	Vegetation manipulation	Extent of mudflat and shallow water in fall (% cover)		
		<66%	66 to 90%	>90%
SEMI	No action	0.95	0.05	0
	Mechanical-chemical	0.9	0.1	0
ESDT	No action	0.7	0.3	0
ESBDT	No action	0.85	0.15	0
	Mechanical-chemical	0.6	0.3	0.1
	Burn	0.5	0.35	0.15
	Disk	0.4	0.4	0.2
LSDT	No action	0.5	0.5	0
LSDF	No action	0.45	0.55	0
	Mechanical-chemical	0.3	0.6	0.1
LSBDT	No action	0.5	0.5	0
	Mechanical-chemical	0.4	0.6	0
	Burn	0.35	0.65	0
	Disk	0.3	0.7	0
EFLR	No action	0.25	0.7	0.05
	Mechanical-chemical	0.15	0.8	0.05

Table 4-2. Conditional probability for extent of mudflat and shallow water in spring, conditional on hydroperiod and vegetation manipulation, for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. See table 2 for abbreviation definitions for hydroperiods. <, less than; >, greater than; %, percent]

Hydroperiod	Vegetation manipulation	Extent of mudflat and shallow water in spring (% cover)		
		<66%	66 to 90%	>90%
SEMI	No action	0.95	0.05	0
	Mechanical-chemical	0.95	0.95	0
ESDT	No action	0.5	0.45	0.05
ESBDT	No action	0.85	0.15	0
	Mechanical-chemical	0.8	0.2	0
	Burn	0.7	0.25	0.05
	Disk	0.6	0.3	0.1
LSDT	No action	0.95	0.05	0
LSDF	No action	0.95	0.05	0
	Mechanical-chemical	0.95	0.05	0
LSBDT	No action	0.95	0.05	0
	Mechanical-chemical	0.95	0.05	0
	Burn	0.95	0.05	0
	Disk	0.95	0.05	0
EFLR	No action	0.25	0.75	0
	Mechanical-chemical	0.25	0.75	0

Table 4-3. Conditional probability for interspersion, conditional on hydroperiod and vegetation manipulation, within impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. See appendix 2 for definition of interspersion levels S, M, and L and table 2 for abbreviation definitions for hydroperiods]

Hydroperiod	Vegetation manipulation	Interspersion		
		S	M	L
SEMI	No action	0	0.05	0.95
	Mechanical-chemical	0	0	1
ESDT	No action	0.7	0.25	0.05
ESBDT	No action	0.55	0.4	0.05
	Mechanical-chemical	0.05	0.25	0.7
	Burn	0.35	0.3	0.35
	Disk	0.85	0.1	0.05
LSDT	No action	0.65	0.25	0.1
LSDF	No action	0.75	0.25	0
	Mechanical-chemical	0.15	0.35	0.5
LSBDT	No action	0.5	0.4	0.1
	Mechanical-chemical	0.05	0.15	0.8
	Burn	0.1	0.25	0.65
	Disk	0.8	0.15	0.05
EFLR	No action	0.1	0.25	0.65
	Mechanical-chemical	0	0.15	0.85

Table 4-4. Conditional probability for seed energy production index, conditional on hydroperiod and vegetation manipulation, for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. See appendix 2 for example Seed Energy Production Index (SEPI) calculations and table 2 for abbreviation definitions for hydroperiods. <, less than; >, greater than]

Hydroperiod	Vegetation manipulation	SEPI		
		<15	15–30	>30
SEMI	No action	0.8	0.2	0
	Mechanical-chemical	1	0	0
ESDT	No action	0.3	0.45	0.25
ESBDT	No action	0.5	0.3	0.2
	Mechanical-chemical	0.6	0.2	0.2
	Burn	0.25	0.45	0.3
	Disk	0.1	0.2	0.7
LSDT	No action	0.2	0.5	0.3
LSDF	No action	0.15	0.35	0.5
	Mechanical-chemical	0.15	0.45	0.4
LSBDT	No action	0.3	0.35	0.35
	Mechanical-chemical	0.5	0.3	0.2
	Burn	0.2	0.35	0.45
	Disk	0.05	0.15	0.8
EFLR	No action	0.05	0.3	0.65
	Mechanical-chemical	0.1	0.3	0.6

Table 4-5. Conditional probability for shorebird-use days in fall, conditional on extent of mudflat and shallow water in fall, for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. <, less than; >, greater than; %, percent]

Extent of mudflat and shallow water in fall (% cover)	Shorebird-use days in fall		
	Low	Moderate	High
<66%	0.85	0.15	0
66–90%	0.1	0.3	0.6
>90%	0.05	0.15	0.8

Table 4-6. Conditional probability for shorebird-use days in spring, conditional on extent of mudflat and shallow water in spring, for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. <, less than; >, greater than; %, percent]

Extent of mudflat and shallow water in spring (% cover)	Shorebird-use days in spring		
	Low	Moderate	High
<66%	0.95	0.05	0.0
66–90%	0.15	0.35	0.5
>90%	0.1	0.2	0.7

Table 4-7. Conditional probability for waterfowl-use days, conditional on interspersion and seed energy production index, that is, habitat state, for impoundment MI-9 at Mattamuskeet National Wildlife Refuge, North Carolina.

[Probabilities in each row sum to unity. See appendix 2 for definitions of interspersion levels S, M, and L. <, less than; >, greater than]

Interspersion	Seed Energy Production Index	Waterfowl-use days		
		Low	Moderate	High
S	Low (<15)	0.25	0.3	0.45
S	Moderate (15–30)	0.2	0.3	0.5
S	High (>30)	0.1	0.15	0.75
M	Low (<15)	0.35	0.3	0.35
M	Moderate (15–30)	0.25	0.3	0.45
M	High (>30)	0.15	0.2	0.65
L	Low (<15)	0.4	0.35	0.25
L	Moderate (15–30)	0.3	0.3	0.4
L	High (>30)	0.2	0.25	0.55

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Appendix 5. Bird-Use Day Estimates

Table 5-1. Predicted fall shorebird-use days in seven impoundments, MI-1 to MI-6 at Mattamuskeet National Wildlife Refuge, North Carolina, for all combinations of hydroperiod and vegetation manipulation.

[Fall predictions for impoundment MI-9 (table 5-2), which were derived from the Bayesian Belief Network model, were scaled to impoundments in this table on the basis of area relative to the area of impoundment MI-9. See table 5-2 for fall shorebird-use days in impoundments MI-8W to MI-11. See table 2 for a description of hydroperiods and vegetation manipulations. Mech., mechanical; ha, hectare]

Hydroperiod	Vegetation manipulation	Impoundment						
		MI-1	MI-2W	MI-2E	MI-3	MI-4	MI-5	MI-6
SEMI	No action	5,969	11,390	20,236	6,184	36,030	4,051	4,619
	Mech.-chemical	6,448	12,303	21,858	6,680	38,918	4,376	4,989
ESDT	No action	8,311	15,860	28,177	8,611	50,168	5,641	6,431
ESBDT	No action	6,901	13,168	23,395	7,150	41,654	4,684	5,340
	Mech.-chemical	9,445	18,022	32,019	9,785	57,009	6,410	7,308
	Burn	10,502	20,041	35,605	10,881	63,394	7,128	8,127
	Disk	11,535	22,011	39,106	11,951	69,627	7,829	8,926
LSDT	No action	10,175	19,416	34,495	10,542	61,417	6,906	7,873
LSDF	No action	10,628	20,281	36,032	11,012	64,154	7,213	8,224
	Mech.-chemical	12,240	23,357	41,497	12,682	73,883	8,307	9,471
LSBDT	No action	10,175	19,416	34,495	10,542	61,417	6,906	7,873
	Mech.-chemical	11,107	21,194	37,654	11,508	67,042	7,538	8,594
	Burn	11,560	22,059	39,191	11,977	69,779	7,846	8,945
	Disk	12,039	22,972	40,814	12,473	72,667	8,171	9,315
EFLR	No action	12,618	24,078	42,777	13,073	76,164	8,564	9,764
	Mech.-chemical	13,550	25,856	45,937	14,039	81,788	9,196	10,485
	Area (ha)	30.5	58.2	103.4	31.6	184.1	20.7	23.6

Table 5-2. Predicted fall shorebird-use days in seven impoundments, MI-8W–MI-11, at Mattamuskeet National Wildlife Refuge, North Carolina, for all combinations of hydroperiod and vegetation manipulation.

[Fall predictions for impoundment MI-9, which were derived from the Bayesian Belief Network model, were scaled to other impoundments based on their area relative to the area of impoundment MI-9. See table 5-1 for fall shorebird-use days in impoundments MI-1–MI-6. See table 2 for a description of hydroperiods and vegetation manipulations. Mech., mechanical; ha, hectare]

Hydroperiod	Vegetation manipulation	Impoundment						
		MI-8W	MI-8E	MI-9	MI-10S	MI-10N	MI-7	MI-11
SEMI	No action	6,752	13,621	23,700	12,153	19,512	4,306	35,873
	Mech.-chemical	7,293	14,713	25,600	13,128	21,076	4,651	38,749
ESDT	No action	9,401	18,966	33,000	16,922	27,168	5,995	49,950
ESBDT	No action	7,806	15,748	27,400	14,051	22,558	4,978	41,473
	Mech.-chemical	10,683	21,552	37,500	19,230	30,873	6,813	56,761
	Burn	11,880	23,966	41,700	21,384	34,331	7,576	63,118
	Disk	13,048	26,323	45,800	23,486	37,707	8,320	69,324
LSDT	No action	11,509	23,219	40,400	20,717	33,261	7,339	61,150
LSDF	No action	12,022	24,254	42,200	21,640	34,743	7,666	63,875
	Mech.-chemical	13,846	27,932	48,600	24,922	40,012	8,829	73,562
LSBDT	No action	11,509	23,219	40,400	20,717	33,261	7,339	61,150
	Mech.-chemical	12,546	25,346	44,100	22,614	36,307	8,012	66,751
	Burn	13,076	26,380	45,900	23,537	37,789	8,339	69,475
	Disk	13,618	27,472	47,800	24,512	39,353	8,684	72,351
EFLR	No action	14,273	28,794	50,100	25,691	41,247	9,102	75,833
	Mech.-chemical	15,327	30,921	53,800	27,589	44,293	9,774	81,433
	Area (ha)	34.5	69.6	121.1	62.1	99.7	22	183.3

Table 5-3. Predicted spring shorebird-use days in seven impoundments, MI-1 to MI-6, at Mattamuskeet National Wildlife Refuge, North Carolina, for all combinations of hydroperiod and vegetation manipulation.

[Spring predictions for impoundment MI-9 (table 5-4), which were derived from the Bayesian Belief Network model, were scaled to impoundments in this table on the basis of area relative to the area of impoundment MI-9. See table 5-4 for spring shorebird-use days in impoundments MI-8W to MI-11. See table 2 for a description of hydroperiods and vegetation manipulations. Mech., mechanical; ha, hectare]

Hydroperiod	Vegetation manipulation	Impoundment						
		MI-1	MI-2W	MI-2E	MI-3	MI-4	MI-5	MI-6
SEMI	No action	3,350	6,392	11,356	3,471	20,219	2,273	2,592
	Mech.-chemical	3,350	6,392	11,356	3,471	20,219	2,273	2,592
ESDT	No action	5,818	11,102	19,724	6,028	35,117	3,949	4,502
ESBDT	No action	3,879	7,401	13,149	4,018	23,412	2,632	3,001
	Mech.-chemical	4,156	7,930	14,088	4,306	25,084	2,820	3,216
	Burn	4,760	9,083	16,138	4,932	28,732	3,231	3,683
	Disk	5,339	10,189	18,101	5,532	32,229	3,624	4,131
LSDT	No action	3,350	6,392	11,356	3,471	20,219	2,273	2,592
LSDF	No action	3,350	6,392	11,356	3,471	20,219	2,273	2,592
	Mech.-chemical	3,350	6,392	11,356	3,471	20,219	2,273	2,592
LSBDT	No action	3,350	6,392	11,356	3,471	20,219	2,273	2,592
	Mech.-chemical	3,350	6,392	11,356	3,471	20,219	2,273	2,592
	Burn	3,350	6,392	11,356	3,471	20,219	2,273	2,592
	Disk	3,350	6,392	11,356	3,471	20,219	2,273	2,592
EFLR	No action	7,077	13,505	23,993	7,333	42,718	4,803	5,476
	Mech.-chemical	7,077	13,505	23,993	7,333	42,718	4,803	5,476
	Area (ha)	30.5	58.2	103.4	31.6	184.1	20.7	23.6

Table 5-4. Predicted spring shorebird-use days in seven impoundments, MI-8W to MI-11, at Mattamuskeet National Wildlife Refuge, North Carolina, for all combinations of hydroperiod and vegetation manipulation.

[Spring predictions for impoundment MI-9, which were derived from the Bayesian Belief Network model, were scaled to other impoundments on the basis of area relative to the area of impoundment MI-9. See table 5-3 for spring shorebird-use days in impoundments MI-1–MI-6. See table 2 for a description of hydroperiods and vegetation manipulations. Mech., mechanical; ha, hectare]

Hydroperiod	Vegetation manipulation	Impoundment						
		MI-8W	MI-8E	MI-9	MI-10S	MI-10N	MI-7	MI-11
SEMI	No action	3,789	7,644	13,300	6,820	10,950	2,416	20,131
	Mech.-chemical	3,789	7,644	13,300	6,820	10,950	2,416	20,131
ESDT	No action	6,581	13,276	23,100	11,846	19,018	4,197	34,965
ESBDT	No action	4,387	8,851	15,400	7,897	12,679	2,798	23,310
	Mech.-chemical	4,701	9,483	16,500	8,461	13,584	2,998	24,975
	Burn	5,384	10,862	18,900	9,692	15,560	3,434	28,608
	Disk	6,040	12,184	21,200	10,871	17,454	3,851	32,089
LSDT	No action	3,789	7,644	13,300	6,820	10,950	2,416	20,131
LSDF	No action	3,789	7,644	13,300	6,820	10,950	2,416	20,131
	Mech.-chemical	3,789	7,644	13,300	6,820	10,950	2,416	20,131
LSBDT	No action	3,789	7,644	13,300	6,820	10,950	2,416	20,131
	Mech.-chemical	3,789	7,644	13,300	6,820	10,950	2,416	20,131
	Burn	3,789	7,644	13,300	6,820	10,950	2,416	20,131
	Disk	3,789	7,644	13,300	6,820	10,950	2,416	20,131
EFLR	No action	8,005	16,150	28,100	14,410	23,134	5,105	42,533
	Mech.-chemical	8,005	16,150	28,100	14,410	23,134	5,105	42,533
	Area (ha)	34.5	69.6	121.1	62.1	99.7	22	183.3

Table 5-5. Predicted nonbreeding waterfowl-use days in seven impoundments, MI-1 to MI-6, at Mattamuskeet National Wildlife Refuge, North Carolina, for all combinations of hydroperiod and vegetation manipulation.

[Nonbreeding waterfowl predictions for impoundment MI-9 (table 5-6), which were derived from the Bayesian Belief Network model, were scaled to impoundments in this table on the basis of area relative to the area of impoundment MI-9. See table 5-6 for predicted nonbreeding waterfowl-use days in impoundments MI-8W to MI-11. See table 2 for a description of hydroperiods and vegetation manipulations. Mech., mechanical; ha, hectare]

Hydroperiod	Vegetation manipulation	Impoundment						
		MI-1	MI-2W	MI-2E	MI-3	MI-4	MI-5	MI-6
SEMI	No action	229,695	438,302	778,702	237,979	1,386,451	155,891	177,731
	Mech.-chemical	223,650	426,768	758,210	231,716	1,349,965	151,789	173,054
ESDT	No action	272,007	519,042	922,147	281,817	1,641,850	184,608	210,471
ESBDT	No action	264,451	504,624	896,532	273,988	1,596,243	179,480	204,471
	Mech.-chemical	244,806	467,138	829,932	253,635	1,477,665	166,147	189,424
	Burn	264,451	504,624	896,532	273,988	1,596,243	179,480	204,624
	Disk	292,155	557,490	990,454	302,692	1,763,468	198,282	226,061
LSDT	No action	274,525	523,848	930,685	284,426	1,657,052	186,317	212,419
LSDF	No action	284,600	543,072	964,839	294,864	1,717,861	193,154	220,215
	Mech.-chemical	264,451	504,624	896,532	273,988	1,596,243	179,480	204,624
LSBDT	No action	272,007	519,042	922,147	281,817	1,641,850	184,608	210,471
	Mech.-chemical	245,813	469,060	833,348	254,679	1,483,746	166,831	190,203
	Burn	261,932	499,818	887,993	271,379	1,581,040	177,770	202,675
	Disk	297,192	567,102	1,007,531	307,911	1,793,873	201,701	229,959
EFLR	No action	272,007	519,042	922,147	281,817	1,641,850	184,608	210,471
	Mech.-chemical	264,451	504,624	896,532	273,988	1,596,243	179,480	204,624
	Area (ha)	30.5	58.2	103.4	31.6	184.1	20.7	23.6

Table 5-6. Predicted nonbreeding waterfowl-use days in seven impoundments, MI-8W to MI-11, at Mattamuskeet National Wildlife Refuge, North Carolina, for all combinations of hydroperiod and vegetation manipulation.

[Nonbreeding waterfowl predictions for impoundment MI-9, which were derived from the Bayesian Belief Network model, were scaled to other impoundments on the basis of area relative to the area of impoundment MI-9. See table 5-5 for predicted nonbreeding waterfowl-use days in impoundments MI-1–MI-6. See table 2 for a description of hydroperiods and vegetation manipulations. Mech., mechanical; ha, hectare]

Hydroperiod	Vegetation manipulation	Impoundment						
		MI-8W	MI-8E	MI-9	MI-10S	MI-10N	MI-7	MI-11
SEMI	No action	259,818	524,155	912,000	467,673	750,837	165,681	1,380,426
	Mech.-chemical	252,981	510,362	888,000	455,366	731,078	161,321	1,344,099
ESDT	No action	307,680	620,710	1,080,000	553,832	889,149	196,201	1,634,715
ESBDT	No action	299,133	603,468	1,050,000	538,439	864,451	190,751	1,589,306
	Mech.-chemical	276,912	558,639	972,000	498,441	800,235	176,581	1,471,244
	Burn	299,133	603,468	1,050,000	538,439	864,451	190,751	1,589,306
	Disk	330,471	666,689	1,160,000	594,847	955,012	210,753	1,755,805
LSDT	No action	310,528	626,457	1,090,000	558,951	897,382	198,018	1,649,851
LSDF	No action	321,924	649,447	1,130,000	579,463	930,314	205,285	1,710,396
	Mech.-chemical	299,133	603,468	1,050,000	538,439	864,451	190,751	1,589,306
LSBDT	No action	307,680	620,710	1,080,000	553,823	889,149	196,201	1,634,715
	Mech.-chemical	278,051	560,938	976,000	500,492	803,528	177,308	1,477,298
	Burn	296,284	597,721	1,040,000	533,311	856,218	188,935	1,574,170
	Disk	336,168	678,183	1,180,000	605,103	971,478	214,368	1,786,078
EFLR	No action	307,680	620,710	1,080,000	553,832	889,149	196,201	1,634,715
	Mech.-chemical	299,133	603,468	1,050,000	538,439	864,451	190,751	1,589,306
	Area (ha)	34.5	69.6	121.1	62.1	99.7	22	183.3

Appendix 6. Genetic Algorithm Approach to Portfolio Analysis

A genetic algorithm (GA) was used to evaluate and select a portfolio of management actions for the 14 impoundments at Mattamuskeet National Wildlife Refuge (MNWR), North Carolina. A GA is a heuristic approach to optimization that is modeled after the process of evolution. It is a computationally efficient approach to assessment when there is a large number of possible solutions (Chinneck, 2015). In this case, there were 16^{14}, or approximately 7.2×10^{16}, possible alternatives. GA may not find the optimal solution (Chinneck, 2015), but it was assumed that GA would locate a portfolio with good performance relative to all possible portfolios. GA was implemented using the package GA (Scrucca, 2013) in the statistical program R 3.2.3 (R Core Team, 2015).

The starting point for GA was a population of 100 potential management action portfolios for the impoundments at MNWR. These portfolios were generated randomly using built-in random sampling functions within R. Each portfolio consisted of a set of 14 real numbers with values between 0 and 16. Real number bins were crosswalked to management actions (table 6-1). The initial population is available from the lead author upon request.

“Fitness” values for resulting management action portfolios in the initial population were determined by the weighted sum of utility for shorebird- and waterfowl-use day objectives. See “Tradeoffs Using Portfolio Analysis” section for equations used to calculate fitness. The management action portfolio with the highest fitness value was designated as the incumbent solution.

To the initial population, a reproduction operator was applied to select and reproduce portfolios on the basis of their fitness values. One hundred portfolios were randomly selected with replacement from the initial population with the probability, P_i, of a portfolio being selected calculated as

$$P_i = \frac{U_i}{\sum_{i=1}^{100} U_i}$$

where

U_i is the fitness value for portfolio i. The newly selected portfolios serve as a mating pool for the next operator.

To the mating pool, a crossover operator was applied. This operator involved randomly selecting two portfolios (parents) from the mating pool, randomly identifying a single common point within both portfolios, and switching the portfolio solutions from that point forward to produce two new portfolios (children) (table 6-2). Crossover results in the creation of a new population of 100 portfolios for further analysis.

The final operator that was applied introduced mutations into the portfolios within the population with a probability of 0.5. On average then, one-half of the real numbers within a portfolio were replaced with a new, randomly selected real number between 0 and 16. The fitness values for these portfolios resulting from the mutation operator were calculated, and if one of the portfolios provided a higher fitness than the incumbent solution, it became the new incumbent solution.

Reproduction, crossover, and mutation operators were applied 10,000 times. Starting with the second iteration, the output from the mutation operator served as the input population for the reproduction operator. After 10,000 iterations, the incumbent solution was selected as the preferred portfolio, given the set of objective weights and budget constraint in place.

References Cited

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R Core Team, 2015, R: a language and environment for statistical computing, v 3.2.3: Vienna, Austria, R Foundation for Statistical Computing, accessed September 1, 2014, at http://www.R-project.org/.

Scrucca, L., 2013, GA: a package for genetic algorithms in R: Journal of Statistical Software, v. 53, p. 1–37.

Table 6-1. Crosswalk between real number bins and their corresponding management action at Mattamuskeet National Wildlife Refuge, North Carolina, defined by the combination of a hydroperiod and vegetation manipulation.

Real number bin	Hydroperiod	Vegetation Manipulation
[0,1]	Semi-permanent	No action
(1,2]		Mechanical-chemical
(2,3]	Early drawdown to ditch top	No action
(3,4]	Early drawdown to below ditch top	No action
(4,5]		Mechanical-chemical
(5,6]		Burn
(6,7]		Disk
(7,8]	Late drawdown to ditch top	No action
(8,9]	Late summer drawdown to ditch top conditions and delayed re-flood	No action
(9,10]		Mechanical-chemical
(10,11]	Late drawdown to below ditch top	No action
(11,12]		Mechanical-chemical
(12,13]		Burn
(13,14]		Disk
(14,15]	Early drawdown, re-flood, late drawdown, re-fill	No action
(15,16]		Mechanical-chemical

Table 6-2. Illustration of crossover operator. Two parent strings are randomly selected from the mating pool, a single crossover point (red line) is randomly identified, and the portfolios are swapped after the crossover point to produce two new portfolios, or children.

[Note that, for illustration purposes, portfolios shown are intentionally truncated to include only 5 of the 14 impoundments at Mattamuskeet National Wildlife Refuge, North Carolina. Actual portfolios evaluated through the genetic algorithm included actions for all impoundments. Real numbers have been converted to corresponding management actions (table 6-1) for ease of interpretation]

Wetland	Parent 1	Parent 2	Child 1	Child 2
MI-1	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk
MI-2W	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk
MI-2E	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk
MI-3	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Late drawdown below ditch top, Disk
MI-4	Late drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Early drawdown below ditch top, Disk	Late drawdown below ditch top, Disk

Appendix 7. Management Action Costs

For the portfolio analysis, a constraint was introduced to ensure that the selected alternative did not exceed budgetary limitations at Mattamuskeet National Wildlife Refuge (MNWR). To evaluate portfolios against the constraint, costs estimates were assigned to each combined hydroperiod and vegetation manipulation in each impoundment.

Depending on the hydroperiod, one or more of three types of cost calculations were included. All hydroperiods required staff hours for activities such as inspecting the impoundment, manipulating water-control structures to permit a gravity drawdown, or operating pumps when necessary to fill or drain the impoundment. To calculate these costs, a staff member's hourly wage was multiplied by the number of hours required to implement a hydroperiod. An hourly wage of $35 per hour was assumed for a maintenance worker hired at a wage grade of 10 (step 5) on the Federal wage rate schedule for the case study region[3]. This wage included benefits at 40 percent. MNWR's Refuge Manager provided estimates of the number of hours required to implement each hydroperiod (Peter Campbell, U.S. Fish and Wildlife Service, oral commun., September 2014).

Additional costs were incurred when a hydroperiod involved drawdown to below ditch top. For these hydroperiods, active pumping is required to empty the volume of water present in ditches within the impoundments. For MI-8W, MI-9, and MI-10S impoundments, ditch volume was directly calculated by using aerial photographs to measure the width and length of ditches and assuming a depth of 3.3 feet (ft; 1 meter [m]). This process was too time intensive to repeat for all impoundments at MNWR. Consequently, it was assumed that ditch volume for each impoundment was equal to 9.4 percent of the full pool volume for the impoundment. This value represented the average of values for MI-8W (11.6%), MI-9 (8.7%), and MI-10S (7.8%). Full pool volume was calculated by multiplying the area of an impoundment by a depth of 1.67 ft (0.51 m). To determine pumping costs for ditches, the pumping cost per acre-foot of water was multiplied by the ditch volume of each impoundment. A pumping cost of $14.94 per acre-foot of water was assumed for a diesel pump with a capacity of 3,000 to 18,000 gallons per minute; this value was extracted from table SOP-4.1 of Loges and others (2014), the monitoring framework for the Integrated Waterbird Management and Monitoring program.

If a hydroperiod included a re-flooding or re-filling of the impoundment, a cost associated with active pumping of water to bring the impoundment to full pool volume was included. For these calculations, the full pool and ditch volumes were included in the calculations; that is, it was assumed that ditches were empty at the start of pumping.

To determine the costs of vegetation manipulations, the per unit area cost estimates in table SOP-4.1 of Loges and others (2014) were used. To the mechanical-chemical manipulation, the subject matter expert assigned the cost associated with spot spraying ($133.26 per hectare [ha]). Spot spraying is frequently used to control undesirable invasive plant species in the impoundments. Soil disturbance within the impoundments is typically accomplished by conventional tillage, so the expert assigned the conventional tillage cost to the disking manipulation ($32.10 per ha). On the basis of MNWR's past history of fire use, the expert assigned prescribed burn costs to the burn manipulation ($65.88 per ha). For each impoundment, per unit area costs for vegetation manipulations were multiplied by impoundment area. At MNWR, mechanical-chemical manipulations typically are triggered when one-half of an impoundment is covered by undesirable vegetation. For this reason, it was assumed that the mechanical-chemical manipulations were applied to only one-half of an impoundment's area.

Cost estimates for each combined hydroperiod and vegetation manipulation for each impoundment are provided in table 7-1.

[3]http://www.cpms.osd.mil/Content/AF%20Schedules/survey-sch/119/119R-16Sep2014.html.

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Loges, B.W., Tavernia, B.G., Wilson, A.M., Stanton, J.D., Herner-Thogmartin, J.H., Casey, J., Coluccy, J.M., Coppen, J.L., Hanan, M., Heglund, P.J., Jacobi, S.K., Jones, T., Knutson, M.G., Koch, K.E., Lonsdorf, E.V., Laskowski, H.P., Lor, S.K., Lyons, J.E., Seamans, M.E., Stanton, W., Winn, B., and Ziemba, L.C., 2014, National protocol framework for the inventory and monitoring of nonbreeding waterbirds and their habitats, an Integrated Water Management and Monitoring Initiative (IWMM) approach: Fort Collins, Colo., Natural Resources Program Center, 97 p.

Table 7-1. Financial costs associated with combined hydroperiods and vegetation manipulations for each impoundment at Mattamauskeet National Wildlife Refuge, North Carolina.

[Costs were calculated as Cost = VC*Area + PC*Volume + 35* hours, where VC is the per hectare cost of a vegetation manipulation and PC is the per acre-foot pumping costs for a hydroperiod. Hourly wage for a maintenance worker implementing a management action was estimated at $35. Mechanical-chemical treatments were applied to only one-half of an impoundment's area. The full pool volume of the impoundment, excluding ditches, equaled the area of the impoundment multiplied by 1.67 feet (20 inches). Ditch volume was assumed to be 9.4 percent of full pool volume. When a hydroperiod entailed only a drawdown to ditch top, volume was equal to full pool volume. Otherwise, cost calculations defined volume using both full pool volume and ditch volume. -, not applicable; ac-ft, acre-foot; ha, hectare]

Hydroperiod	Vegetation manipulation	$ per ha (VC)	$ per ac-ft (PC)	Hours	Mattamuskeet impoundments						
					MI-1	MI-2W	MI-2E	MI-3	MI-4	MI-5	MI-6
Semi-permanent	No action	-	-	6	210	210	210	210	210	210	210
	Mechanical-chemical	133.26	-	6	2,242	4,088	7,100	2,316	12,477	1,589	1,782
Seasonal, early drawdown to ditch top	No action	-	-	10	350	350	350	350	350	350	350
Seasonal, early drawdown to below ditch top	No action	-	14.94	16	736	897	1,158	743	1,625	680	696
	Mechanical-chemical	133.26	-	16	2,769	4,775	8,048	2,848	13,891	2,059	2,269
	Burn	65.88	-	16	2,746	4,731	7,970	2,824	13,753	2,043	2,251
	Disk	32.1	-	16	1,715	2,765	4,477	1,757	7,534	1,344	1,454
Seasonal, late drawdown to ditch top	No action	-	-	6	210	210	210	210	210	210	210
Seasonal, late summer drawdown to ditch top conditions and delayed re-flood	No action	-	14.94	18	2,683	4,548	7,590	2,757	13,022	2,023	2,219
	Mechanical-chemical	133.26	14.94	18	4,715	8,425	14,480	4,863	25,289	3,403	3,791
Seasonal, late drawdown to below ditch top	No action	-	14.94	16	526	687	948	533	1,415	470	486
	Mechanical-chemical	133.26	-	16	2,559	4,565	7,838	2,638	13,681	1,849	2,059
	Burn	65.88	-	16	2,536	4,521	7,760	2,614	13,543	1,833	2,041
	Disk	32.1	-	16	1,505	2,555	4,267	1,547	7,324	1,134	1,244
Seasonal, early drawdown, re-flood, late drawdown, re-fill	No action	-	14.94	26	2,963	4,828	7,870	3,037	13,302	2,303	2,499
	Mechanical-chemical	133.26	-	26	4,995	8,705	14,760	5,143	25,569	3,683	4,071
			Area (ha)		30.5	58.2	103.4	31.6	184.1	20.7	23.6
			Full pool volume (ac-ft)		126	239.7	425.8	130	758.2	85.2	97.2
			Ditch volume (ac-ft)		11.9	22.5	40	12.2	71.3	8	9.1

[*] Disking is infeasible in MI-11, so the cost was set to be prohibitively expensive, given considered budgets.

Table 7-1. Financial costs associated with combined hydroperiods and vegetation manipulations for each impoundment at Mattamauskeet National Wildlife Refuge, North Carolina.—Continued

[Costs were calculated as Cost = VC*Area + PC*Volume + 35* hours, where VC is the per hectare cost of a vegetation manipulation and PC is the per acre-foot pumping costs for a hydroperiod. Hourly wage for a maintenance worker implementing a management action was estimated at $35. Mechanical-chemical treatments were applied to only one-half of an impoundment's area. The full pool volume of the impoundment, excluding ditches, equaled the area of the impoundment multiplied by 1.67 feet (20 inches). Ditch volume was assumed to be 9.4 percent of full pool volume. When a hydroperiod entailed only a drawdown to ditch top, volume was equal to full pool volume. Otherwise, cost calculations defined volume using both full pool volume and ditch volume. -, not applicable; ac-ft, acre-foot; ha, hectare]

Hydroperiod	Vegetation manipulation	$ per ha (VC)	$ per ac-ft (PC)	Hours	Mattamuskeet impoundments						
					MI-8W	MI-8E	MI-9	MI-10S	MI-10N	MI-7	MI-11
Semi-permanent	No action	-	-	6	210	210	210	210	210	210	210
	Mechanical-chemical	133.26	-	6	2,509	4,847	8,279	4,348	6,853	1,676	12,423
Seasonal, early drawdown to ditch top	No action	-	-	10	350	350	350	350	350	350	350
Seasonal, early drawdown to below ditch top	No action	-	14.94	16	760	963	1,260	919	1,137	687	1,620
	Mechanical-chemical	133.26	-	16	3,058	5,600	9,329	5,057	7,780	2,153	13,834
	Burn	65.88	-	16	3,032	5,548	9,238	5,010	7,705	2,137	13,695
	Disk	32.1	-	16	1,867	3,197	5,147	2,912	4,337	1,393	1×10^{6}*
Seasonal, late drawdown to ditch top	No action	-	-	6	210	210	210	210	210	210	210
Seasonal, late summer drawdown to ditch top conditions and delayed re-flood	No action	-	14.94	18	2,952	5,315	8,781	4,810	7,341	2,111	12,968
	Mechanical-chemical	133.26	14.94	18	5,251	9,952	16,850	8,948	13,984	3,577	25,182
Seasonal, late drawdown to below ditch top	No action	-	14.94	16	550	753	1,050	709	927	477	1,410
	Mechanical-chemical	133.26	-	16	2,848	5,390	9,119	4,847	7,570	1,943	13,624
	Burn	65.88	-	16	2,822	5,338	9,028	4,800	7,495	1,927	13,485
	Disk	32.1	-	16	1,657	2,987	4,937	2,702	4,127	1,183	1×10^{6}*
Seasonal, early drawdown, re-flood, late drawdown, re-fill	No action	-	14.94	26	3,232	5,595	9,061	5,090	7,621	2,391	13,248
	Mechanical-chemical	133.26	-	26	5,531	10,232	17,130	9,228	14,264	3,857	25,462
			Area (ha)		34.5	69.6	121.1	62.1	99.7	22	183.3
			Full pool volume (ac-ft)		142.1	286.6	498.7	255.8	410.6	90.6	754.9
			Ditch volume (ac-ft)		13.4	26.9	46.9	24	38.6	8.5	71

*Disking is infeasible in MI-11, so the cost was set to be prohibitively expensive, given considered budgets.

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