STRUCTURED DECISION MAKING FOR COASTAL MANAGED WETLANDS IN DELAWARE

A report from a USFWS/USGS structured decision making workshop held at the National Conservation Training Center, Shepherdstown, WV, 13-17 September 2010 and subsequent analysis

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Decision Problem Definition

There are approximately 4,050 hectares of managed wetlands in coastal Delaware under the stewardship of Delaware Department of Natural Resources and Environmental Control (DNREC) and the United States Fish and Wildlife Service (USFWS). These wetlands vary in how water levels are manipulated and what the source water is. They also vary in their vulnerability to coastal pressures and sea level rise as some are directly on the bayshore while others are more inland with a salt marsh to buffer them from the effects of severe storms. They have the capacity to be managed for multiple objectives but wintering waterfowl and hunting tend to be the driving force behind annual management and each is managed independent of the others. A group of collaborating stakeholders face the decision problem of how best to manage these impoundments across the landscape in a coordinated fashion that addresses multiple objectives. The difficulty of developing sound management decisions in the coastal zone is exacerbated by uncertainty related to climate change and rising sea levels. Therefore, we require a framework to guide landscape-scale decisions, one that is not only robust to scientific uncertainty about the rate of sea level rise (SLR), but also will achieve maximum benefits across multiple objectives, over the next 40 years.

The decision support framework we present below allows for potentially shifting management scenarios where on the landscape impoundments are maintained, built, or let revert to tidal systems as sea level rise makes it too costly to maintain and manage them. Legal authority is spread across several agencies including USFWS, DNREC, and Delaware Department of Transportation (DELDOT). In addition, the adjacent landowners and various interest groups influence decision making. Decisions are made at several time frames: Seasonal water level adjustments, 3-5 year impoundment management plans, and longer range plans such as Comprehensive Conservation Planning the National Wildlife Refuge System.

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We selected four impoundments from those in the DE coastal zone. We used this subset of impoundments (Prime Hook NWR Unit 3, Bombay Hook NWR Raymond Pool, Little Creek North, and Logan Lane South) to develop a prototype decision model. The purpose of our analysis was to find the best combination of management actions to achieve multiple objectives in the face of climate change uncertainty. Although we limited the number of impoundments used in our model to allow completion of the prototype in the time available during the workshop, there is no other practical limit on the number of management units and objectives that could be considered.

Background

Legal, regulatory, and political context

With multiple management agencies as stakeholders, our decisions may be influenced by multiple legal and regulatory frameworks. The two National Wildlife Refuges in Delaware—Bombay Hook and Prime Hook—were established under specific legislation with explicit purposes. In addition, the Refuge System has a regulatory framework for deciding upon management alternatives. Similarly, DNREC has a regulatory framework for managing impoundments as well. Some of the DNREC impoundments are held in partial ownership with DElDOT, in which case the regulatory framework of DELDOT also impacts decision making in collaborative efforts. Finally, adjacent landowners have interest in the management of impoundments with regard to potential flooding issues, and there are a number of special interest groups concerned about impoundment management for reasons that include mosquito control, hunting, birding, fishing, and other recreational activities.

Ecological context

The USFWS recently found that Bombay Hook, Prime Hook, and Chincoteague NWRs have more waterfowl, waders, and shorebirds than any other refuge in USFWS Region 4 or 5. At a flyway scale, these impoundments are relatively important as well, holding a large percentage of the flyway population. It is safe to assume that DNREC-owned impoundments provide similar and/or contributory ecological benefit to the USFWS impoundments. At a state-wide scale, the impoundments are economically important with hunting estimated to bring in several million dollars to Delaware. However, maintaining impoundments carries a cost, and managing for multiple objectives involves ecological trade-offs that are difficult to quantify and have daunting uncertainty.

Decision Structure

Objectives

Our initial list of fundamental objectives included:

- Maximize Breeding Marsh Birds
- **Maximize Roosting Red Knots and Spring Migrating Shorebirds**
- Maximize Breeding Shorebirds (e.g., Black-necked Stilt)
- **Maximize Migrating and Wintering Waterfowl**
- Maximize Fall Migrating Shorebirds
- Maximize Breeding Waterfowl
- **Maximize Juvenile Fish Populations**
- Maintain Furbearer populations at a desired level (e.g., Muskrat)
- Maximize Recreational Use
- Minimize Cost

To complete a prototype decision model in the time allowed, it was necessary to select a subset of objectives from the list above. We originally selected a subset of five objectives, including mosquito control. However, as the team (which included a mosquito control representative) worked through the initial prototype, it became clear that the mosquito control objective was more appropriately considered as part of the cost of management. Subsequently, this objective was incorporated into the cost objective. This left three objectives to include in our prototype: 1) maximizing migrating and wintering waterfowl, 2) maximizing roosting Red Knots, and 3) maximizing juvenile fish populations (Fig. 1). Remaining objectives will be included in the next prototype if necessary.

Measurable attributes were chosen for each objective: 1) duck use days between October and March, 2) average number of Red Knots roosting in each wetland, and 3) ratio of catch with a cast net inside a water control structure to outside the water control structure.

Objective weights, which sum to one, reflect relative importance in multi-objective decision problems and are used to facilitate tradeoffs among objectives. Weights for objectives were elicited from the expert panel using a modified swing weighting technique (Hammond et al. 1999). Our experts decided that equal weight on all three objectives was not appropriate, and that for this exercise, red knot roosting habitat was the most important objective. Objective weights for waterfowl and fish objectives were assigned relative to the red knot objective. Final weights were 0.44, 0.36, and 0.20 for red knots, waterfowl, and fish populations, respectively (Fig. 1).

Action Alternatives

Impoundments are managed over several different time horizons. Seasonally, managers choose between several actions, such as flushing, drawdown, and flooding. These actions are determined by the impoundment management plan which prescribes various flood stages to meet annual and seasonal management objectives. For example, an impoundment may be maintained at full pool during winter, gradually drawn down to provide food for migrating waterfowl in the spring, kept low to maximize plant growth during the summer, followed by slow flooding in late summer through fall to spread food availability for waterfowl over the fall season. This also maximizes diversity of water levels; different annual water level regimes are best for different groups of species, and no one regime can maximize benefits for all objectives. On a longer time horizon, sea level rise is becoming an ever more important issue compromising the ability to manage water levels. In this case, managers have alternatives including raising dikes, replacing/enlarging water control structures, creating openings in dikes to increase water exchange and tidal flow, abandoning impoundments, and building new impoundments.

Developing management actions for each impoundment.—We listed 5-6 management actions that were feasible for each impoundment (Table 1). We began with three management actions in the form of three different annual schedules for water level manipulations, which were motivated by our objectives. Management action 1 was an annual water regime considered beneficial to migrating and wintering waterfowl (Fig. 2). Action 2 was an annual water regime tailored to roosting Red Knots (Fig. 3). Action 3, "DE Saline", was an annual water regime considered a compromise solution to achieve multiple benefits (Fig. 4). Actions 1-3 were generic in the sense that each action could be applied in any one of the impoundments. Note also that these water regimes will result in some level of benefits for each of the objectives, not just the motivating objective. For example, action 1 is designed to maximize benefits for waterfowl, but Red Knots and other shorebirds are still expected to use the impoundment, just not as often as expected under action 2 (Red Knot regime).

We also specified restoration actions that were designed to improve water control and make it possible to continue to achieve multiple objectives despite rising sea level. Restoration actions were specific to a particular impoundment. For example, action 4 for Prime Hook NWR Unit 3 was to raise the levee and replace the water control structure, and then manipulate water levels according to the "waterfowl water regime" (Table 1). Action 4 is thus expected to restore and maintain water level control in the management unit as sea level continues to rise. We included other restoration and management actions to reduce impacts of sea level rise specific for Bombay Hook, Little Creek, and Logan Lane (Table 1).

Ongoing sea level rise has impacted management decision making and will continue to do so. No single water regime will be optimal for all objectives, but it

may be possible to develop a portfolio approach in which different impoundments are managed to maximize different objectives, and overall, all objectives are met across the landscape. Considerations include the number of existing impoundments, their locations on the landscape, effectiveness of current and future water level control, and potential areas for new impoundments.

Portfolios of actions.—Decision makers choose a management action (Table 1) for each of the impoundments in the decision framework. The collection of management actions for all impoundments is the "management portfolio." Using an optimization routine, it is possible to identify a management portfolio that maximizes the sum of benefits from all impoundments, while meeting cost and other constraints. A Pareto efficiency analysis—which provides decision makers with a rich set of options rather than merely one optimal solution—can also serve as decision support (see *Pareto Analysis* below).

Predictive Model

We relied on conceptual models and expert opinion for our predictive modeling. First, our expert panel constructed an influence diagram for each of our objectives (Fig. 5-7). Influence diagrams are conceptual models that link management actions with objectives or threats (Clemen 1996). In our model, migrating and wintering waterfowl abundance is largely a function of food availability, size of the fall flight, and human disturbance (Fig. 5). Roosting Red Knot abundance is a function of roost habitat availability, distance to foraging areas, tide height, predation risk, and the size of the stopover population (Fig. 6). Finally, juvenile fish populations are a function of water exchange and quality, year class size, and food availability (Fig. 7).

Second, our expert panel made predictions for each of the management actions (Table 1) with respect to each of our objectives. Predictions were specified in the measureable attributes identified in our objectives hierarchy (Fig. 1). During this elicitation, the panel used the influence diagrams to guide predictions. For example, an impoundment in closer proximity to a Red Knot feeding area would be predicted to attract more birds than one that is farther away.

Parameter uncertainty.—Experts provide best judgment estimates for each of the objectives in response to each possible action. Predicting a single value, however, overestimates confidence in that particular value, and does not accommodate uncertainty related to environmental variation or incertitude in the conceptual models. Therefore, our panel provided not one point estimate (or "score") for each action, but at least two predictions and probability values for each to capture variability in outcomes (Fig. 8). Probability values, which sum to 1.0, express the likelihood of a particular outcome. From these discrete probability density functions, we calculated "expected value" (see "*Single Dimension Value Functions*" below) which is robust to parameter uncertainty in our conceptual model.

For example, waterfowl abundance at Prime Hook Unit 3 when using Action 1, was estimated to be 10,000 with probability 0.2, 20,000 with probability 0.3, and 30,000 with probability 0.5. The expected waterfowl abundance is calculated as

$$0.2 \times (10{,}000) + 0.3 \times (20{,}000) + 0.5 \times (30{,}000) = 23{,}000 \text{ (Fig. 8, upper left).}$$

Finally, our expert panel made predictions for three time periods: 10, 20, and 30 years into the future (Figure 9). This allows explicit incorporation of anticipated changes at the impoundments into management decisions, and how to best allocate financial resources for long term benefits. The 30 year time frame was selected as a period we could reasonably expect existing impoundments to be maintained and to function given the stresses of sea level rise.

Decision Analysis

Tradeoffs Using Single Dimension Value Functions

Each action (Table 1) results in a predicted outcome in terms of our three objectives: waterfowl abundance, red knots, and juvenile fish populations. Predictions were made using units of duck use days, number of roosting Red Knots, and a ratio of cast net catch inside and outside of the impoundment (i.e., our measureable attributes; Fig.1). Clearly, it is not possible to simply sum these measurements, either as a measure of overall benefit or as a way to make tradeoffs among objectives. To make tradeoffs among objectives in a multi-objective problem, it is necessary to convert predicted responses to a common scale. We converted predicted responses to a 0-1 scale for each objective using single dimension value functions (Kirkwood 1997):

where x is a predicted response, $v(x)$ is the associated "value" between 0 and 1, *Low* is the lowest score, and *High* is the highest score for the objective. The value function above applies where higher scores are more desirable (i.e., an increasing value function; decreasing value functions are similar).

We created a single dimension value function for each of our objectives. The shape of the value function allows decision makers to express relative value of outcomes (Fig. 10; Kirkwood 1997). For example, the expected score for waterfowl in Prime Hook Unit 3 under action 1 was 23,000 duck use days, which

would result in a value of 0.77 using our single dimension value function (Fig. 10).

Given the predicted scores (x), associated probabilities p(x), and a value function v(x), we calculated expected value (EV) under each action as:

$$EV(\text{action } i) = v(x)*p(x).$$

For example, waterfowl abundance at Prime Hook Unit 3 when using Action 1, was estimated to be 10,000 with probability 0.2, 20,000 with probability 0.3, and 30,000 with probability 0.5. Using our value function for waterfowl abundance (Fig. 9), the v(x) values for 10,000, 20,000, and 30,000 duck use days are, respectively 0.33, 0.67, and 1.0. The expected value of waterfowl abundance at Prime Hook Unit 3 as a result of action 1 is calculated as

$$EV(\text{action 1 at Unit 3}) = 0.2 \times (0.33) + 0.3 \times (0.67) + 0.5 \times (1.0) = 0.77. \qquad (1)$$

Model Uncertainty: Multiple working hypotheses about sea level rise

Rising sea levels will influence the ability to achieve management objectives in coastal wetlands. This is compounded by considerable uncertainty in the rate of sea level rise, and subsequent impacts on management decision making. To address climate change uncertainty, we incorporated two models of sea level rise in our decision framework. The first model was formed under the hypothesis that sea level rise will be equal to 0.5 m over 100 years, which is the estimated current rate of sea level rise (Current SLR). Due to the uncertainty in long-term sea level rise, our second model was created under the hypothesis that sea level rise will be equal to 1 m over 100 years (i.e., an “Accelerated SLR”).

Model weights for our two hypotheses about sea level rise, which sum to one, reflect credibility or degree of support for each hypothesis. Model weights were assigned by group consensus. The Current SLR hypothesis received a model weight of 0.7; the Accelerated SLR hypothesis received a weight of 0.3.

The expected increases in sea level at 10, 20, and 30 years in the future were calculated:

Hypothesis	10 years	20 years	30 years
Model 1 “Current” SLR (0.5 m/100 yr)	5 cm (2 in)	10 cm (4 in)	15 cm (6 in)
Model 2 “Accelerated” SLR (1 m/100 yr)	10 cm (4 in)	20 cm (8 in)	30 cm (12 in)

The expert panel then described change in management capabilities under different amounts of sea level rise:

- Prime Hook, Unit 3: At 10 cm (4 in) sea level rise, partial control; at 15 cm (6 in), no control; at 30 cm (12 in), road/dike will be overtopped.

- Bombay Hook, Raymond Pool: Good control at all levels under consideration.

- Little Creek, North Unit (Mahon): At 10 cm (4 in), partial control; at 20 cm (8 in), no control; and at 30 cm (12 in), dike overtopped.

- Logan Lane, South Unit: At 5 cm (2 in), partial control; at 15 cm (6 in), no control; at 20 cm (8 in), dike overtopped.

Using our conceptual models of the system (Fig. 5-7), and our evaluation of changes in management capabilities over time (above), our expert panel made predictions under both the Current SLR (model 1) and the Accelerated SLR (model 2), at 10, 20, and 30 years in the future (Fig. 9).

For example, under model 1, expected waterfowl abundance at Little Creek North with action 1 is 680, 485, and 330 duck use days at 10, 20, and 30 years, respectively (Fig 9). We calculated expected value of action *i* over the entire 30 year period as the sum of expected values at year *j* = 10, 20, and 30 years:

, (2)

where is expected value at year *j* of action *i*. Finally, we calculated expected value under model uncertainty as

, (3)

where is model weight for model *k*, and is expected value of action *i* under model *k*.

Optimization Procedure

Our optimization routine is designed to maximize the sum of management benefits for all actions included in the portfolio, while meeting constraints (e.g., cost restriction). Management benefit for action *i* is defined as the weighted sum of expected value for all three objectives:

, (4)

where is objective weight for objective *l*, and is expected value under model uncertainty of action *i* with respect to objective *l*.

We used linear programming as implemented in Solver of Microsoft Excel© to

subject to constraints,

where I_i is a decision variable equal to 1 if action i is included in portfolio, and 0 otherwise; $n_{actions}$ is the number of management actions considered, and y_i is cost in dollars of management action i.

Pareto Efficiency Frontier.—Optimization based on linear programming identifies a single optimal portfolio given a set of constraints (e.g., cost constraints). In many cases a graphical solution such as a Pareto efficiency frontier is also helpful for decision guidance.

Uncertainty

We incorporated uncertainty in our model predictions using discrete probability density functions (see *Parameter uncertainty* above). We also incorporated climate change uncertainty (see *Model Uncertainty – Multiple working hypotheses about sea level rise* above).

There are several aspects of environmental variation influencing this decision framework. For example, weather and vegetative response are not known completely. There is also uncertainty about how long a given impoundment can provide maximum value under a given management regime. Observations suggest that there may be a need to occasionally allow full flushing to "re-invigorate the impoundment."

Results

It is possible to use our decision tool in two ways. First, we can evaluate costs and benefits of custom portfolios by simply setting the decision variable in our spreadsheet to include actions that we select for each impoundment. Evaluating custom portfolios in this way relies on equations 1-4, but does not employ the optimization routine described above. Second, it is possible to set cost and other

constraints and use the optimization routine to identify optimal portfolios of actions. The framework is extremely flexible and can incorporate a wide variety of constraints other than cost to tailor portfolios to any combination of objectives and constraints desired by decision makers.

We evaluated six portfolios (4 custom portfolios and two identified with cost constraints):

Portfolio A: minimum cost actions for each impoundment.
Portfolio B: action 1 (waterfowl water regime) in all impoundments.
Portfolio C: action 2 (red knot water regime) in all impoundments.
Portfolio D: action 3 (DE saline water regime) in all impoundments.
Portfolio E: cost constraint of $100,000.
Portfolio F: cost constraint of $250,000.

Note: Water regimes are described above; see *Developing management actions for each impoundment* in Action Alternatives. Water regimes are also depicted in Figures 2-4.

Portfolio	Management Benefit	Cost
A	1.32	$26,000
B	1.39	$40,000
C	1.65	$32,000
D	0.98	$31,000
E	1.69	$40,000
F	1.69	$238,000

Portfolio A, using the least expensive action for each wetland, would cost $26,000 overall and produce the second lowest estimate of management benefits (1.32). Portfolio B (Action 1, waterfowl water regime, in all impoundments) is of course more expensive ($40,000) than portfolio A, but management benefits increase to 1.39. Portfolio C is created by selecting Action 2 (red knot water regime) for all impoundments. Portfolio C is less expensive ($32,000) than portfolio B and results in greater overall benefits (1.65). [Action 2 provides benefits for Red Knots and waterfowl.]

The cost of portfolio D (Action 3, DE Saline water regime, in all impoundments) is similar in cost to portfolio C, but results in the smallest estimate of overall benefits (0.98).

Portfolio E, generated using the optimization routine with a cost constraint of $100,000, results in a portfolio similar to C: action 2 (red knot water regime) is selected for all wetlands except Prime Hook Unit 3, where action 1 (waterfowl water regime) is implemented. This change results in increased estimated benefits (1.69) and a marginal cost increase ($40,000), but easily satisfied the cost constraint.

If the available budget is increased to $250,000, Portfolio F is the optimal combination of management actions: action 2 (red knot water regime) at Logan Lane South and Little Creek North; action 1 (waterfowl water regime) at Prime Hook Unit 3, and action 4 (raise water control structure at year 20, plus red knot water regime) at Bombay Hook Raymond Pool. **Benefits do not increase above portfolio E, suggesting that our predictive model does not adequately capture the benefits of this expensive management action.**

A Pareto efficiency analysis provides a graphical solution that evaluates five management portfolios simultaneously (Fig. 12.) To create a Pareto efficiency frontier, portfolio benefits (y-axis) are plotted as a function of portfolio costs (x-axis). In this diagram, portfolios to the left and top of the plot are more effective and more efficient than portfolios to the right and bottom. In our example, portfolios A, C, and E lie on the efficiency frontier. For a given budget (point on the x-axis) these portfolios provide maximum benefits across the landscape. Portfolios B and D provide inferior benefits for a given budget and are considered suboptimal. Portfolio D (action 3 DE Saline in all wetlands) is most beneficial to fish populations but because this objective receives less weight than other objectives, this portfolio is less effective at meeting multiple objectives.

It is also instructive to evaluate management benefits toward each of our objectives individually for portfolios of interest (Fig. 13). Portfolios B (Fig. 13A) and C (Fig. 13B) provide a relatively even distribution of benefits for all three objectives. Most of the management benefit of Portfolio D (Fig. 13C), however, results from benefits to fish populations. Given that fish populations receive less weight than other objectives (Fig. 1), it is not surprising that this portfolio is not as effective as Portfolios C or E (Fig. 12D).

Discussion

Value of decision structuring.—Structuring the decision provided an explicit way to deal with multiple, competing objectives and uncertainty. By allowing each team member to see the effect of different objectives and outcomes on the final decision, it was easier to make modifications and see where additional work would best be applied and what new information would be most beneficial in reducing uncertainty.

Further development required.—Additional work will be needed to develop the remaining objectives, identify the full suite of impoundments under consideration, and gather data on impoundment flood stages before this can be fully useful for planning and managing Delaware's impoundments.

When the decision support framework fully incorporates this new information, the insights gained from this will be used to inform management decisions in developing a state-wide impoundment management plan. Additional experts need

to be brought into the decision process as the state develops its revised impoundment management plan. Funding is already in hand to do the remaining work.

Prototyping process.—The time pressure of developing a prototype in one week was useful in that it allowed the team members to focus on the process and quickly see how all the components fit together and interacted. However, it required taking shortcuts and breaking the problem into two stages. An initial prototype, completed in the first three days, proved the concept of developing an optimal strategy for impoundment management across the landscape, but did not include climate change. The second prototype (presented in this report), which incorporates climate change and uncertainty of habitat use by target species, was completed after the initial workshop. Even with this limitation, because of the highly structured approach, it was easy to see where simplifications were required, and what would need to be added in the future to complete a more realistic model and solution. The value of building a complete prototype during the workshop was that we were able to quickly establish proof of concept, so that committing resources for the future work could be justified.

The primary technique for building predictive models relied on expert elicitation. It was invaluable to have a team that was willing to work together, seek appropriate simplifications, and find ways to move forward in a limited amount of time. By referring back to our decision structure, and how the various pieces fit together, no real wrong turns were taken.

Recommendations

The core problem is to how to achieve the maximum benefits from coastal wetlands in Delaware that are managed for multiple competing objectives in the face of uncertainty associated with climate change, over the next 30 years. No single impoundment can meet all objectives every year. This suggests a portfolio approach to the problem is warranted. We incorporated anticipated sea level rise due to climate change under two scenarios. We then estimated the consequences of different management options under these two scenarios to provide greatest management benefits across the landscape. Our approach results in decision guidance that is robust to climate change uncertainty.

Insights from this analysis can inform management decision making and be used to help develop a state-wide management plan for coastal managed wetlands. The prototype will need to be expanded into a completed framework with parameters based upon additional data and expertise. In addition, the decision model will be only one tool for developing a state-wide management plan. Other considerations such as state budgets and public input will need to be considered before final decisions are made.

Literature Cited

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Hammond J. S., Keeney R. L., Raiffa H. 1999. Smart Choices: A Practical Guide to Making Better Life Decisions. Broadway Books, New York.

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List of Tables

Table 1. Management actions (1-6 for each impoundment) and costs.

Table 1. Potential management actions and costs for each managed wetland. wcs = water control structure.

Location/Unit	Management Action	Cost ($K)
Prime Hook NWR		
Unit 3	1. Waterfowl water regime	$23
Unit 3	2. Red Knot water regime	$15
Unit 3	3. DE Saline water regime	$10
Unit 3	4. Raise levee, replace wcs, & (1)	$1,200
Unit 3	5. Raise levee, replace wcs, & (2)	$1,200
Unit 3	6. Raise levee, replace wcs, & (3)	$1,200
Bombay Hook NWR		
Raymond Pool	1. Waterfowl water regime	$2
Raymond Pool	2. Red Knot water regime	$2
Raymond Pool	3. DE Saline water regime	$1
Raymond Pool	4. Raise levee, replace wcs, & (1)	$200
Raymond Pool	5. Raise levee, replace wcs, & (2)	$200
Logan Lane		
South unit	1. Waterfowl water regime	$10
South unit	2. Red Knot water regime	$10
South unit	3. DE Saline water regime	$13
South unit	4. Construct new 150 ac impoundment, pumping, & (1).	$700
South unit	5. Construct new 150 ac impoundment, pumping, & (2).	$700
South unit	6. Construct new 150 ac impoundment, pumping, & (3).	$700
Little Creek		
North (Mahon)	1. Waterfowl water regime	$5
North (Mahon)	2. Red Knot water regime	$5
North (Mahon)	3. DE Saline water regime	$7
North (Mahon)	4. Replace wcs, dike work, sediment control, & (1).	$800
North (Mahon)	5. Replace wcs, dike work, sediment control, & (2).	$800
North (Mahon)	6. Replace wcs, dike work, sediment control, & (3).	$800

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Figure 1. Final objectives hierarchy with weights and measurable attributes.

Figure 2. Schematic showing water regime throughout the year to maximize benefits for migrating and wintering waterfowl (Action 1).

Figure 3. Schematic for annual water regime (action) to maximize roost habitat for spring migrant red knots (Action 2).

Figure 4. Schematic of water regime referred to as “DE Saline” (Action 3).

Figure 5. Influence diagram (conceptual model) for migrating and wintering waterfowl.

Figure 6. Influence diagram (conceptual model) for spring migrant red knots.

Figure 7. Influence diagram (conceptual model) for juvenile fish populations.

Figure 8. Selected discrete probability density functions used to incorporate parameter uncertainty in predictive models.

Figure 9. Sea level rise and management actions. Model uncertainty and benefits over time.

Figure 10. Value functions v(x).

Figure 11. Spreadsheet approach to linear programming.

Figure 12. Pareto efficiency frontier.

Figure 13. Management benefit by objective.

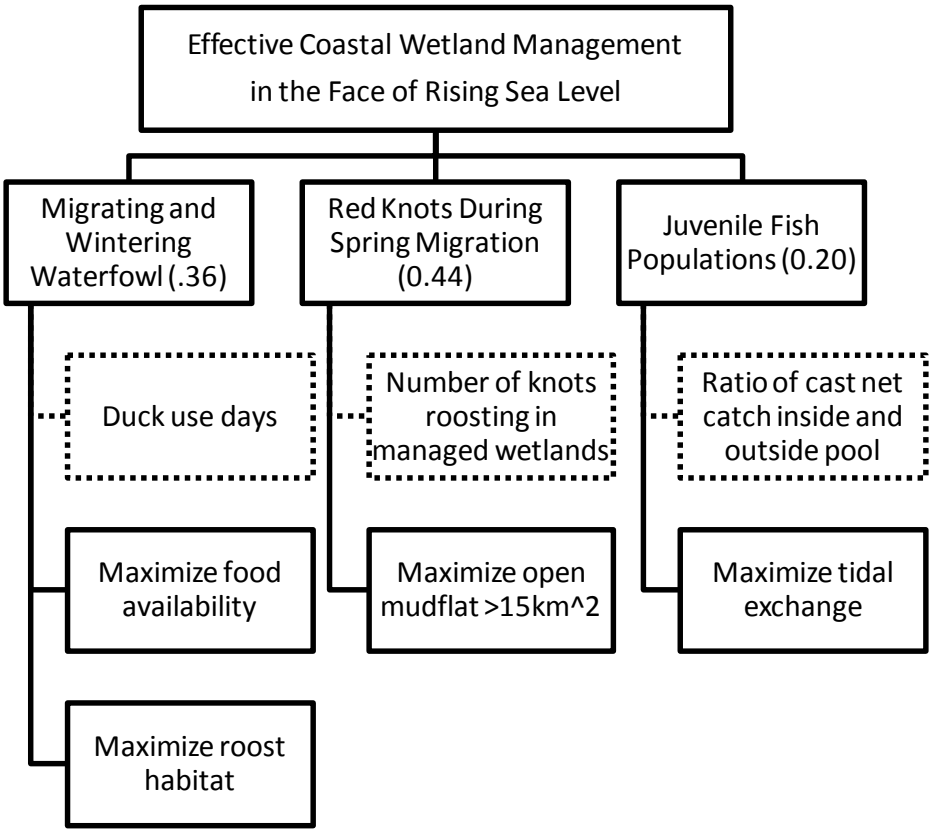

Figure 1. Final objectives hierarchy with weights and measurable attributes. Measurable attributes are indicated with dotted lines.

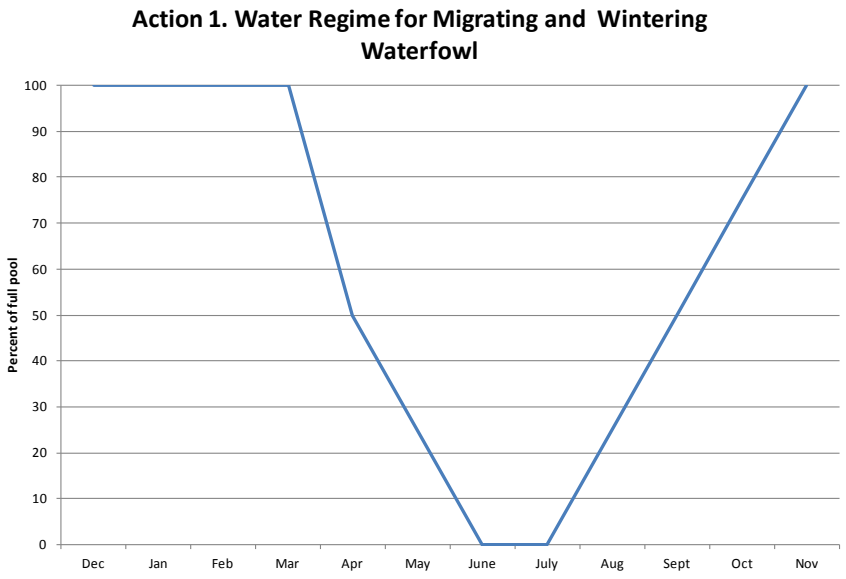

Figure 2. Schematic showing water regime throughout the year to maximize benefits for migrating and wintering waterfowl (Action 1). [brief rationale and intended effects] Full pool during winter, gradual drawdown for migrants in the spring, maximize plant growth during the summer, slow flooding late summer through fall to spread food availability over the fall season and to maximize diversity of water levels.

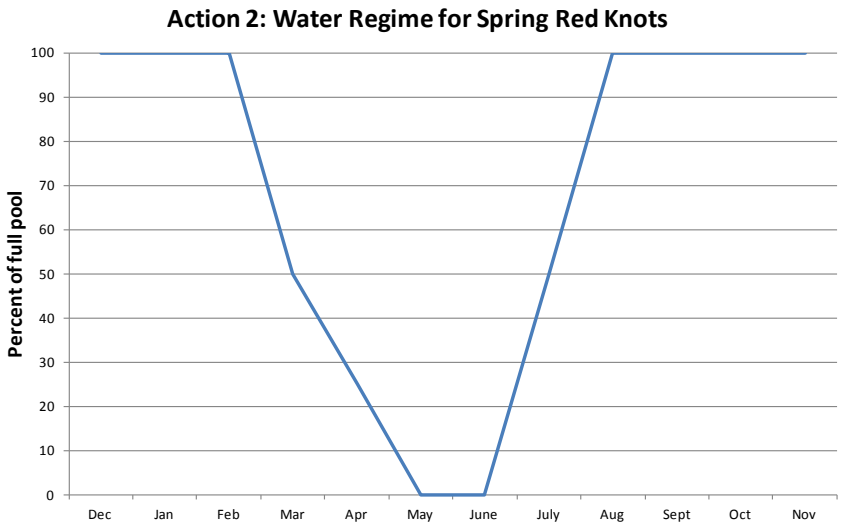

Figure 3. Schematic for annual water regime (action) to maximize roost habitat for spring migrant red knots (Action 2). [brief rationale and intended effects] Focus is on providing mudflats during May, and quickly filling again after May to minimize plant growth on mudflats. Controlling water levels during Late Summer through March are largely irrelevant, other than to minimize encroachment of vegetation onto mudflats.

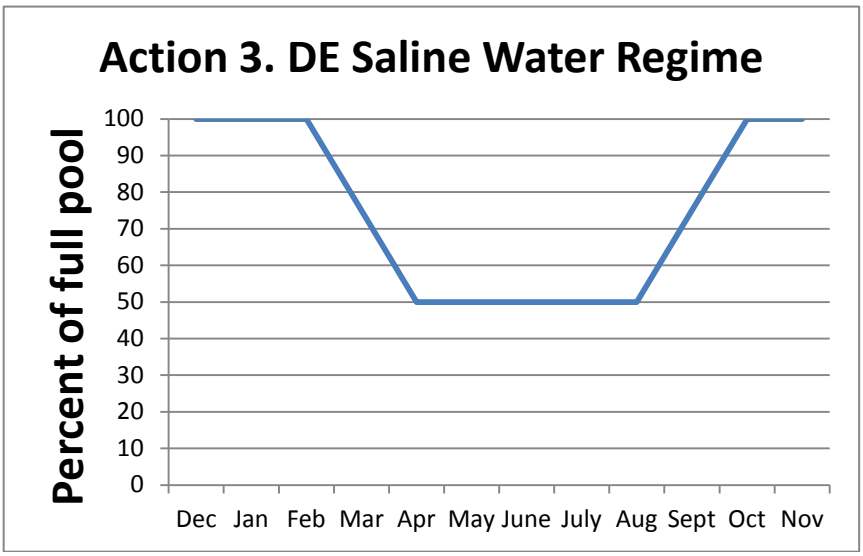

Figure 4. Schematic of water regime referred to as "DE Saline" (Action 3). This regime was designed to balance waterfowl, fish, and mosquito objectives originally (a compromise solution).

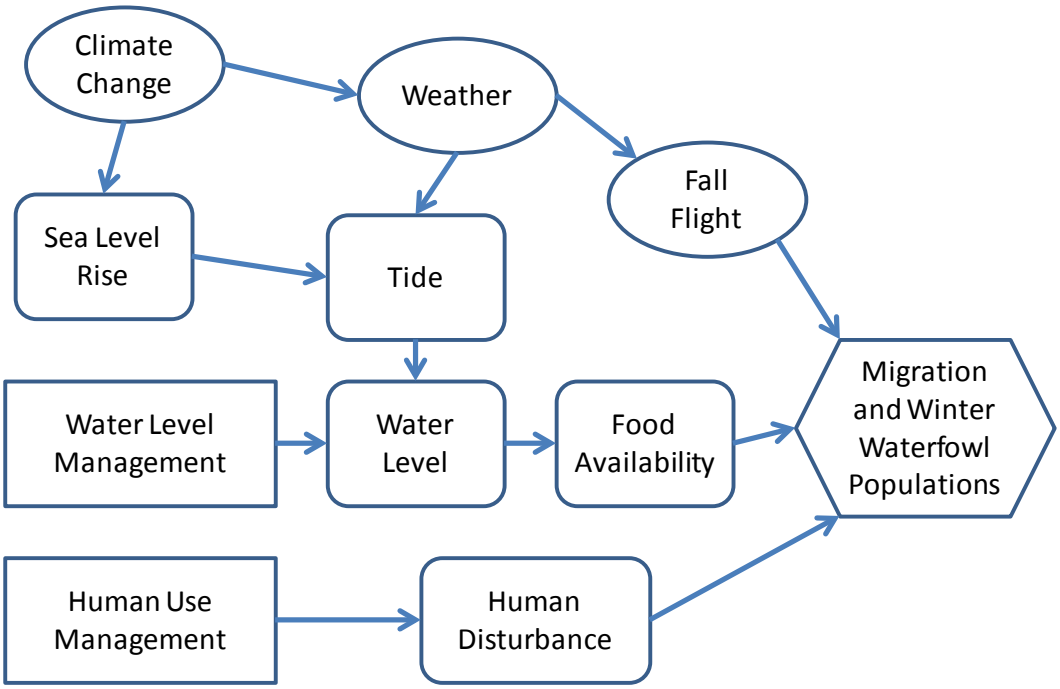

Figure 5. Influence diagram for migrating and wintering waterfowl. In this conceptual model, rectangles with square corners are management decision nodes; oval nodes represent stochastic processes; rectangles with rounded corners indicate intermediate calculations; and hexagons represent outcomes (e.g., objectives).

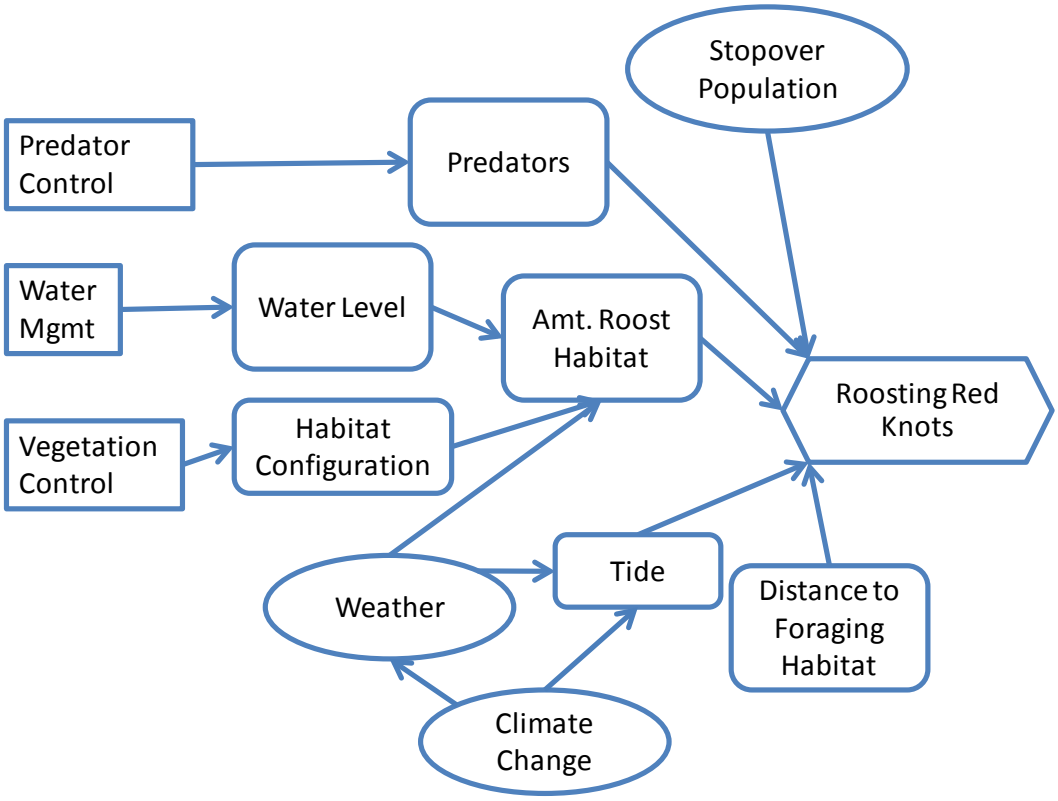

Figure 6. Influence diagram for spring migrant red knots. In this conceptual model, rectangles with square corners are management decision nodes; ovals represent stochastic process nodes; rectangles with rounded corners indicate intermediate calculations; and hexagons represent outcomes (e.g., objectives).

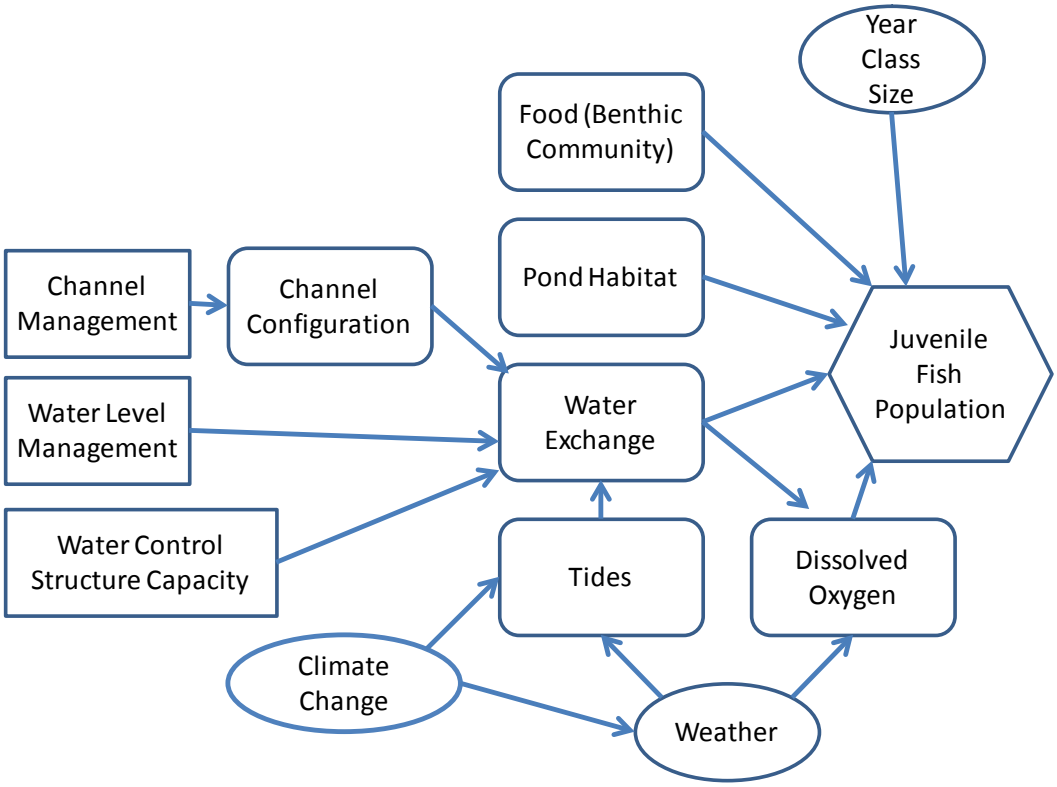

Figure 7. Influence diagram for juvenile fish populations. In this conceptual model, rectangles with square corners are management decision nodes; oval nodes represent stochastic processes; rectangles with rounded corners indicate intermediate calculations; and hexagons represent outcomes (e.g., objectives).

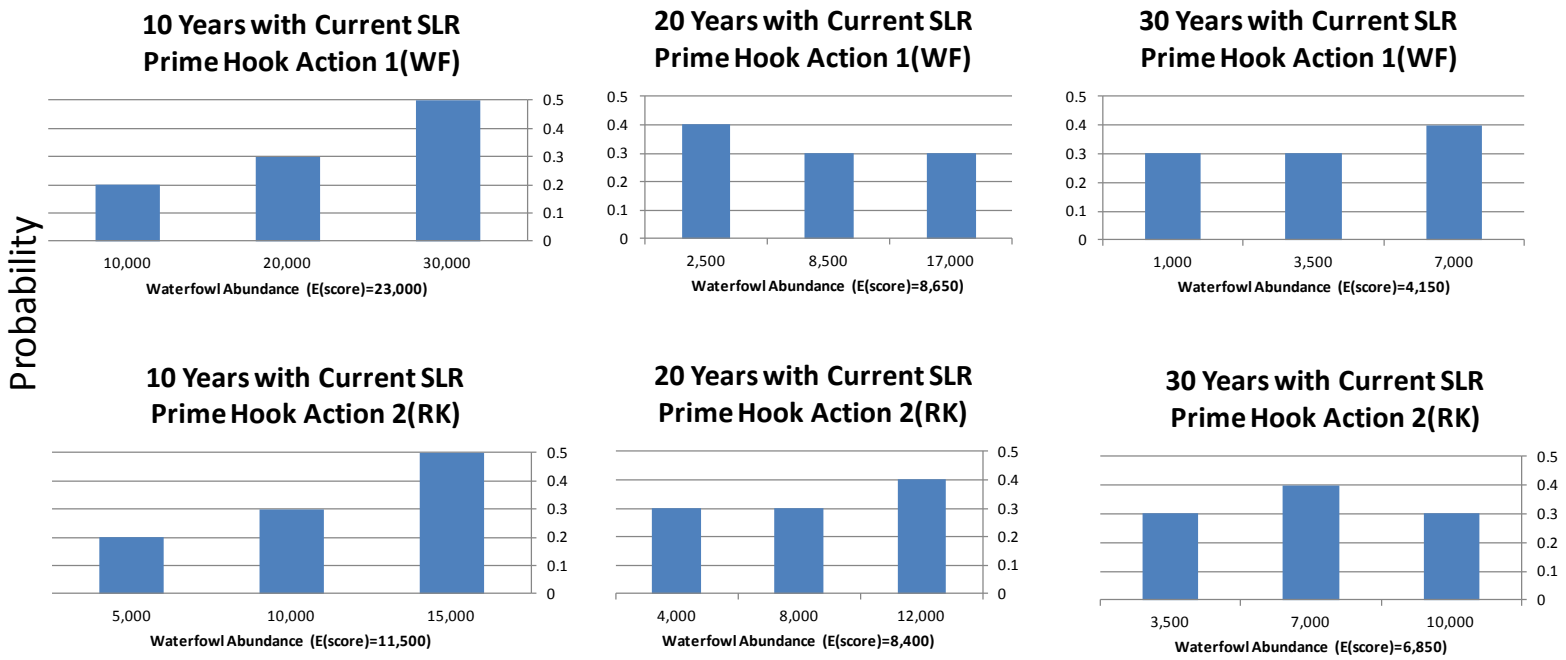

Figure 8. Selected discrete probability density functions used to incorporate parameter uncertainty in predictive models. Scores and probability values were elicited from the expert panel.

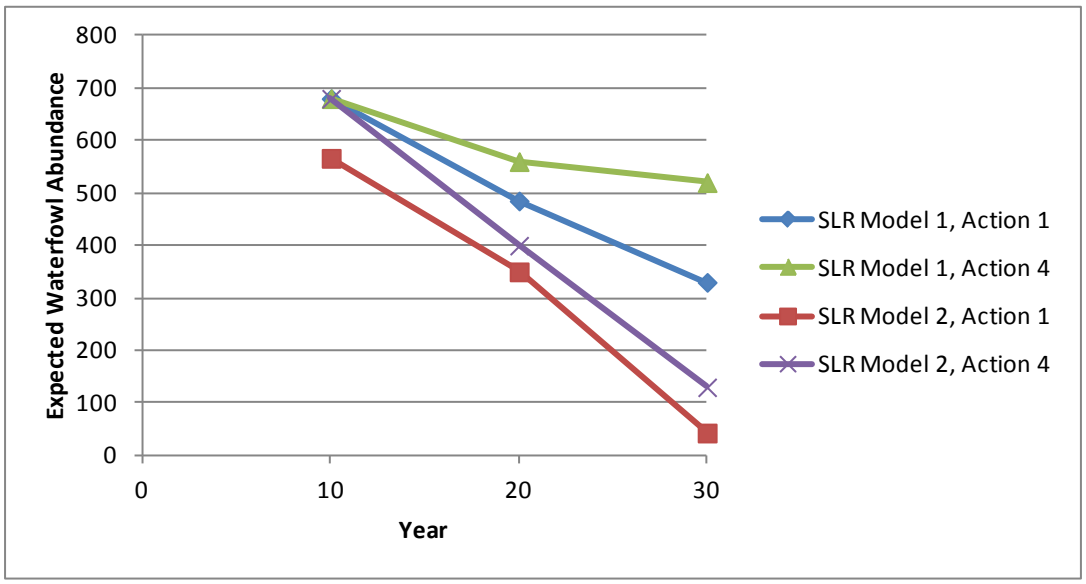

Figure 9. Sea level rise, actions, and expected waterfowl abundance, Little Creek North (Mahon).

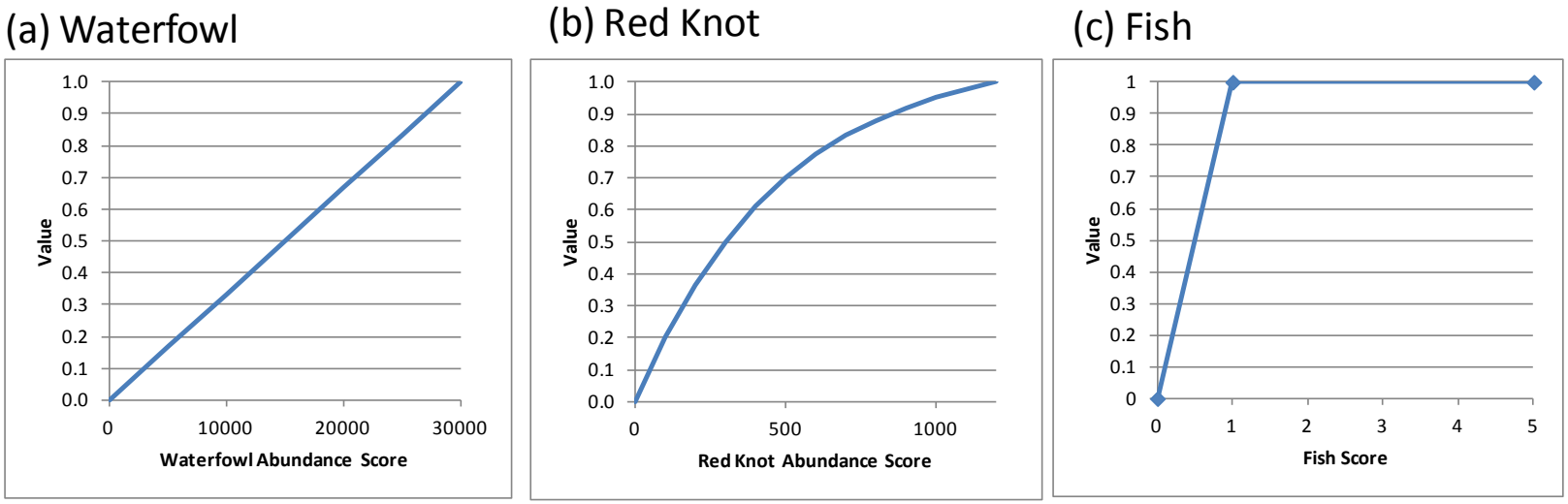

Figure 10. Value functions

Mgt. Unit	Management Action	WEV Waterfowl	WEV Knots	WEV Fish	Portfolio	Management Benefit	Cost ($K)
Unit III PH	A1: Waterfowl water regime	0.3619	0.1234	0.1255	1	0.6108	$23
Unit III PH	A2: Red Knot water regime	0.2744	0.1623	0.1255	0	0.5622	$15
Unit III PH	A3 DE Saline water regime	0.1269	0.0269	0.1255	0	0.2793	$10
Unit III PH	A4: Raise levee, replace wcs, & (A1)	0.6494	0.0748	0.1255	0	0.8497	$1,200
Unit III PH	A5: Raise levee, replace wcs, & (A2)	0.2996	0.2251	0.1255	0	0.6501	$1,200
Unit III PH	A6: Raise levee, replace wcs, & (A3)	0.2177	0.0376	0.1255	0	0.3807	$1,200
Raymond	A1: Waterfowl water regime	0.0369	0.0000	0.0000	0	0.0369	$2
Raymond	A2: Red Knot water regime	0.0191	0.0402	0.0000	0	0.0593	$2
Raymond	A3: DE Saline water regime	0.0126	0.0000	0.0000	0	0.0126	$1
Raymond	A4: Raise wcs @ 20 yrs, & (A1)	0.0382	0.0000	0.0000	0	0.0382	$200
Raymond	A5: Raise wcs @ 20 yrs, & (A2)	0.0191	0.0402	0.0000	1	0.0593	$200
LoganS	A1: Waterfowl water regime	0.0217	0.2688	0.0983	0	0.3887	$10
LoganS	A2: Red Knot water regime	0.0209	0.4159	0.0988	1	0.5355	$10
LoganS	A3: DE Saline water regime	0.0152	0.0021	0.2234	0	0.2406	$13
LoganS	A4: Construct new 150 ac imp, pumping, & (A1)	0.0756	0.2812	0.0072	0	0.3640	$700
LoganS	A5: Construct new 150 ac imp, pumping, & (A2)	0.0442	0.3239	0.0072	0	0.3752	$700
LoganS	A6: Construct new 150 ac imp, pumping, & (A3)	0.0415	0.0000	0.0072	0	0.0487	$700
LittleCrk	A1:Waterfowl water regime	0.0163	0.2776	0.0588	0	0.3527	$5
LittleCrk	A2: Red Knot water regime	0.0119	0.4226	0.0588	1	0.4933	$5
LittleCrk	A3: DE Saline water regime	0.0082	0.0000	0.4382	0	0.4465	$7
LittleCrk	A4: Replace wcs, dike work, sediment control, & (A1)	0.0191	0.3739	0.0308	0	0.4239	$800
LittleCrk	A5: Replace wcs, dike work, sediment control, & (A2)	0.0137	0.5610	0.0308	0	0.6055	$800
LittleCrk	A6: Replace wcs, dike work, sediment control, & (A3)	0.0087	0.0000	0.4396	0	0.4484	$800
						1.6989	$238
						1.6989	
					Waterfowl	0.4138	
					Red Knot	1.0021	
					Fish	0.2831	
						Cost Constraint	$250

Figure 11. A spreadsheet approach to optimization of management benefits for a portfolio of actions (linear programming with Solver in Excel).

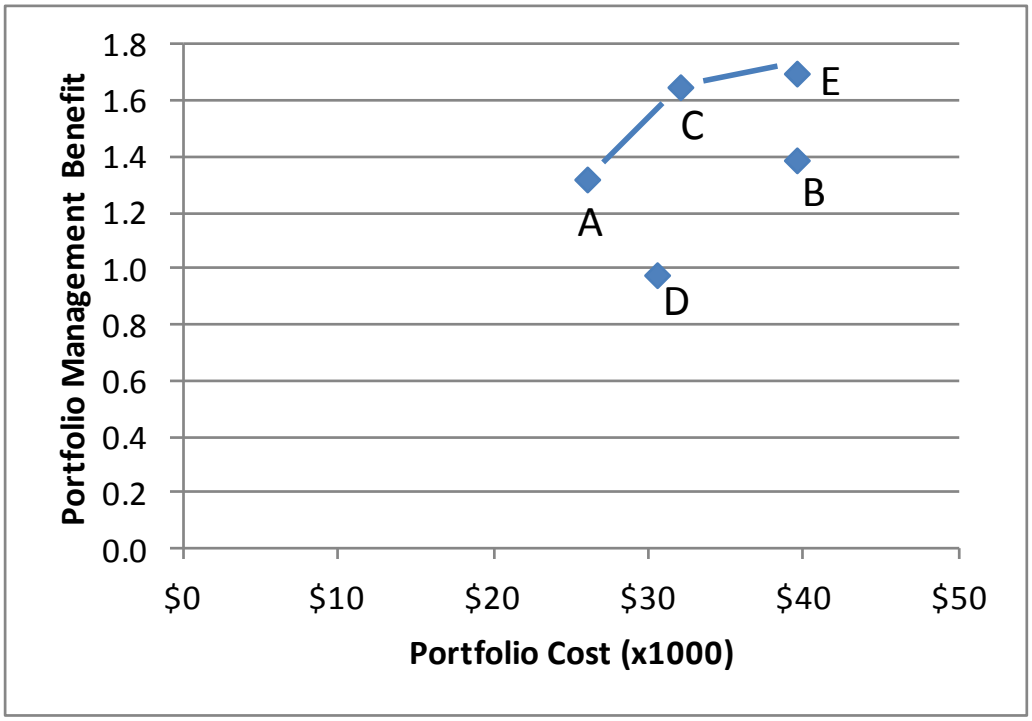

Figure 12. Pareto efficiency frontier. Portfolio A: minimum cost actions in each impoundment; Portfolio B: action 1 (waterfowl water regime) in all impoundments; Portfolio C: action 2 (red knot water regime) in all impoundments; Portfolio D: DE saline water regime in all impoundments; Portfolio E: cost constraint of $100,000.

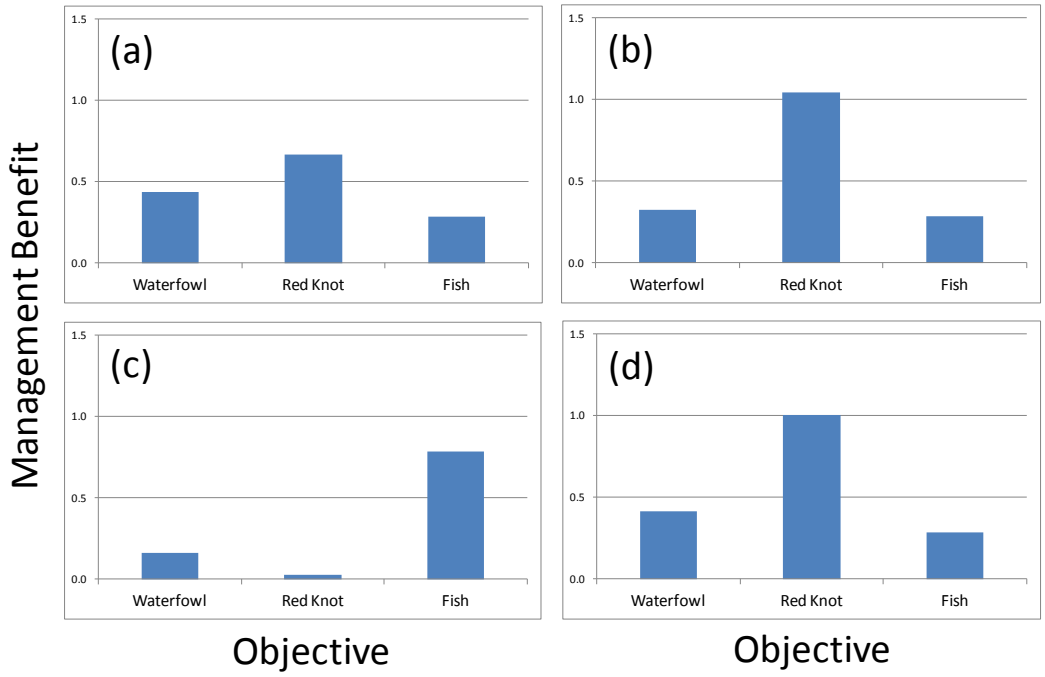

Figure 13. Comparison of benefits from selected portfolios for each objective. Each bar shows expected management benefit for a given objective.

Portfolio benefits resulting from (a) Action 1 [waterfowl water regime] in all impoundments, (b) Action 2 [Red Knot water regime] in all impoundments, (c) Action 3 [DE Saline water regime] in all impoundments, and (d) optimal actions in each impoundment under a $100K cost constraint. Waterfowl and Red Knot water regimes (a,b) result in a relatively even distribution of benefits across objectives. DE Saline water regime (c) results total benefits that are lower than (a) and (b) and skewed toward fish populations.

Total benefits in (d), the best portfolio under a $100K cost constraint, are greater than (a), (b), or (c). The actions in this portfolio include Action 2 (Red Knot water regime) in all impoundments except Prime Hook Unit 3, where Action 1 (waterfowl water regime) is implemented.