Systems Modeling to Improve the Hydro-Ecological Performance of Diked Wetlands

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Key Points

- Include responsive water and vegetation components in a wetland systems model
- Model results suggest synergistic strategies to improve bird habitat
- Important to jointly consider hydrology and vegetation system components

Abstract

Water scarcity and invasive vegetation threaten arid-region wetlands and wetland managers seek ways to enhance wetland ecosystem services with limited water, labor, and financial resources. While prior systems modeling efforts have focused on water management to improve flow-based ecosystem and habitat objectives, here we consider water allocation and invasive vegetation removal that jointly target the concurrent hydrologic and vegetation habitat needs of priority wetland bird species. We formulate a composite weighted usable area for wetlands (*WU*) objective function that represents the wetted wetland surface area that provides suitable water depth and vegetation cover conditions for priority bird species. Maximizing the *WU* is subject to constraints such as water balance, hydraulic infrastructure capacity, invasive vegetation growth

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and control, and a limited financial budget to control vegetation. We apply the model at the Bear River Migratory Bird Refuge on the Great Salt Lake, Utah, compare model-recommended management actions to past Refuge water and vegetation control activities, and find that managers can double the area of suitable habitat by more dynamically managing water levels and removing invasive vegetation early in the growing season. Scenario and sensitivity analyses show the importance to jointly consider hydrology and vegetation system components rather than only the hydrological component.

Keywords: Water management, Systems optimization model, Wetland habitat, Invasive vegetation removal, Phragmites, Migratory birds, Utah

1. Introduction

Wetland ecosystems provide critical habitat for wildlife, water quality improvement, and flood mitigation yet in arid regions of the world these ecosystem services are threatened by water scarcity and invasive species [*Downard and Endter-Wada*, 2013; *Euliss et al.*, 2008; *Zedler and Kercher*, 2004; *Zedler and Kercher*, 2005]. The timing, duration, and depth of flooding drive many aspects of wetland structure and function [*Mitsch and Gosselink*, 2007], and together with wetland vegetation, determine the suitability of wetlands for wildlife habitat. And yet, it is often difficult to manage wetland vegetation and hydrology together to enhance ecosystem services [*Euliss et al.*, 2008].

This difficulty arises because the two activities are often undertaken independently of one-another. For example, managers often manipulate the hydrologic regime as a proxy to alter wetland species biology such as reproduction, growth, and survival [*Batzer and Sharitz*, 2014; *Mitsch and Gosselink*, 2007]. Water-level changes help maintain wetland biodiversity [*Zedler and Kercher*, 2005] including to provide habitat for bird communities [*Kaminski et al.*, 2006; *Ma et al.*, 2010].

In contrast, managers control or remove invasive vegetation [Zedler and Kercher 2004] such as *Phragmites australis* (common reed, hereafter *Phragmites*) to directly alter wetland plant distributions. *Phragmites* distribution and abundance has increased dramatically in North America over the past 150 years [*Kettenring et al.*, 2012; *Saltonstall*, 2002] and is a serious problem for wetland managers in part because it outcompetes other plant species considered to be more important as food or cover for wildlife [*Hazelton et al.*, 2014]. *Phragmites* can also reduce species diversity by limiting available nesting habitat and food quality for birds [*Chambers et al.*, 1999; *Zedler and Kercher*, 2004]. Thus, *Phragmites* control – applying herbicides followed by burning or mowing – can improve habitat quality [*Ailstock et al.*, 2001; *Hazelton et al.*, 2014]. At the same time, control activities require time, staff, and financial resources that in many cases are limited [*Kettenring and Adams*, 2011] and must be coordinated with water management actions [*Ma et al.*, 2010]. Thus, managers often want to know where, when, and how to apply scarce water, labor, and financial resources to improve wetland habitat [*Downard and Endter-Wada*, 2013].

Systems optimization models can help connect these hydrological, ecological, management, and other system components and show how to allocate scarce resources to improve one or multiple management objectives [*Hof and Bevers*, 2002; *Loucks et al.*, 2005]. When included, environmental and ecological system model components are often specified as static constraints such that water allocations must obey a minimum in-stream flow value to guarantee fish survival [*Draper et al.*, 2003; *Vogel et al.*, 2007]. A small but growing literature is moving beyond constraint methods to define, embed, and optimize one or multiple ecological objectives in a systems model. For example, a multi-objective optimization model selected the magnitude and frequency of stream flows that maximize fish population under water availability constraints [*Cardwell et al.*, 1996]. A mixed integer model recommended water depth and salinity management strategies to maximize avian abundance within fixed basins in San Francisco Bay tidal areas [*Stralberg et al.*, 2009]. A non-linear integer programming model recommended investments in operation and flow control structures to minimize changes of the natural flow regime in the Murray River, Australia [*Higgins et al.*, 2011]. *Szemis et al.* [2014] used ant colony optimization to identify environmental flows in the Murray basin that maximized ecological scores for key indicator species in wetland and floodplain areas. And in the Connecticut River basin, *Steinschneider et al.* [2013] used penalty-based linear programming to minimize the departure of reservoir storage levels, releases, and instream flows from target ranges established to generate hydropower, supply water, and maintain aquatic fish and invertebrate habitat. Although the reviewed modeling efforts span diverse aquatic, floodplain, and wetland ecosystems, each formulated water as the sole time-varying, managed resource that influences a flow-based ecological objective function and desired outcome. Yet, in these and other ecosystems, ecological outcomes depend both on the abiotic factor water and biotic factors such as vegetation communities that vary through time and in response to managers' control and harvesting actions.

In this study, we include water levels and wetland vegetation as responsive components in a systems optimization model for diked wetlands that simultaneously identifies water allocation and invasive vegetation removal actions that maximize a composite weighted usable area for wetlands (*WU*) objective. This *WU* objective represents the wetland surface area that provides suitable water depth and vegetation cover conditions for priority bird indicator species. Maximization of *WU* is subject to constraints such as water availability and water balance, hydraulic infrastructure capacity, invasive vegetation growth, and a limited financial budget to control vegetation. We apply the model at the Bear River Migratory Bird Refuge, Utah (hereafter, the Refuge), which is located on the northeast shore of the Great Salt Lake, Utah and managed by the U.S. Fish and Wildlife Service to provide feeding, resting, and breeding grounds for several globally-significant populations of migratory birds. We compare model-recommended water and vegetation management actions to managers' historical activities to suggest strategies to improve migratory bird habitat. Scenario and sensitivity analyses show the importance of jointly considering hydrology and invasive vegetation system components rather than only the hydrological component. The work is a product of a six year collaboration with Refuge managers and also demonstrates a participatory approach to address long-standing challenges to formulate and populate systems models with tractable objective functions, constraints, and data that can inform ecosystem management.

2. Modeling Framework and Formulation

Systems modeling offers a general framework to identify and connect interdependent system components, study interactions, and recommend management strategies to better achieve management goals. To implement the framework, the analyst works through six progressive phases to:

Phase 1. Describe the management goal(s).

Phase 2. Identify metrics that quantify progress towards achieving goal(s) identified in phase one.

Phase 3. Identify actions managers can take to affect progress towards achieving the goal(s).

Phase 4. Mathematically relate management actions to the metrics.

Phase 5. Identify constraints that limit actions managers can take.

Phase 6. Implement and solve the optimization model. The model adjusts decision variable values to maximize (or minimize) the performance metrics while simultaneously satisfying constraints on actions that managers can take.

The phase 1 description of management goals and associated priority species typically guides specifics at subsequent steps such as species habitat needs and the hydrologic and other actions managers can take to influence habitat. And while prior systems modeling work has managed for fish, mussels, periphyton, waterfowl, and other species in intensively managed aquatic, floodplain, and wetland systems, modeling efforts have only used flow-based habitat objectives tied to hydrologic variables such as water depth, velocity, flow duration, or departure from the natural flow-regime [*Cardwell et al.*, 1996; *Higgins et al.*, 2011; *Loucks*, 2006; *Steinschneider et al.*, 2013; *Stralberg et al.*, 2009; *Szemis et al.*, 2014]. Here, we consider migratory birds within diked wetlands and their concurrent habitat needs for water and vegetation to feed, rest, overwinter, and rear offspring. In diked wetlands, managers can regulate water (through canals, gates, and weirs) and manipulate vegetation through burning, mowing, herbicide application, and grazing to maintain and improve bird habitat (Figure 1).

Below, we describe each phase of the modeling framework as undertaken at the Refuge and present the resulting general model formulation for a diked wetland system where one or more interconnected wetland units are managed over a fixed time horizon for one or more priority species having concurrent habitat needs for water and/or vegetation. Sections 3, 4, and 5 present the data used to populate the model for the Refuge, model results, and recommendations to improve management.

2.1. Wetland Management Goals

The overall Refuge management goal—identified through participatory meetings with managers and review of Refuge management plans [*Olson*, 2007; *Olson et al.*, 2004]—is to enhance wetland habitat for priority migratory bird species. Priority species represent a subset of the some 250 bird species that occur at the Refuge and that managers prioritized because either species (i) populations are present at the Refuge in globally significant numbers, or (ii) habitat needs encompass the needs of other species. Enhancing habitat for priority bird species also promotes a broader set of Refuge management goals including to promote birding, fishing, wildlife viewing, conservation, and other recreation opportunities within the Refuge. Enhancing habitat for priority species differs from other ecological management efforts that instead try to restore the natural water regime or ecological state [*Higgins et al.*, 2011; *Steinschneider et al.*, 2013]. In diked wetlands such as at the Refuge, hydrology, soils, and vegetation are so altered and disturbed compared to the pre-European settlement state that complete or incremental return to that state is not feasible or desirable [*Downard and Endter-Wada*, 2013]. Instead, managers focus on the more immediate and reachable goal to improve habitat for key species.

2.2 Performance Metric

To quantify progress towards reaching the management goal to enhance habitat for priority bird species, we identified the key feeding, resting, and breeding activities priority migratory bird species undertake at the Refuge, activity timings, and habitat requirements for those activities. Habitat requirements include pools of water of sufficient depth to feed and rest as well as wetland vegetation cover in which to feed, rest, and breed. The concurrent water and vegetation habitat requirements are species-specific. We then developed a weighted unit area for wetlands (*WU*) metric that describes the available wetted surface area for priority bird species to undertake specified activities. The *WU* sums weighted products of species-specific suitability indicators for water depth and invasive vegetation cover habitat attributes by the wetted area. The *WU* is quantified in simple areal units (i.e., m^2) that are easy to communicate to external audiences, observe in the field, and calculate spatially across diked wetland units and through time (Eq. 1).

$$WU = \sum_{t,w} \left[\left(\frac{\sum_s sw_{t,s} \cdot HW_{t,w,s} \cdot HV_{t,w,s}}{\sum_s sw_{t,s}} \right) \cdot a_w\left(S_{t,w}\right) \right] \qquad (1)$$

Where $sw_{t,s}$ is the weight in time t for species s (unitless), $HW_{t,w,s}$ and $HV_{t,w,s}$ are suitability indices for, respectively, water depth and invasive vegetation habitat attributes in time t and wetland unit w for species s (unitless), and $a_w(S_{t,w})$ is the wetted surface area in time t in wetland unit w (m^2) that is a function (a_w) of the water storage volume in time t in unit w ($S_{t,w}$; m^3). Here and subsequently, we specify time t in monthly steps because Refuge staff plan, schedule, and monitor management actions at monthly intervals. The *WU* metric does not include temporal discounting because of the monthly time spacing and short planning horizon (generally one year at the Refuge).

The water depth and invasive vegetation cover habitat suitability indices *HW* and *HV* take values from 0 (poor) to 1 (excellent) habitat quality to describe the capacity of each individual habitat attribute to support selected bird species, and their use follows two decades of work to define habitat quality for fish, alligators, birds, algae, and other wildlife species [*Tarboton et al.*, 2004]. The multiplication of the two suitability indices in Eq. 1 means priority bird species require both suitable water depth and invasive vegetation cover conditions; that water and vegetation are separate and concurrent but non-substitutable habitat requirements.

Weighting the habitat suitability indices by species and the wetted area adapts to diked wetlands a widely used weighting approach for evaluating in-stream flow needs [*Cardwell et al.*, 1996; *Hardy*, 2005; *Payne*, 2003]. Here, the species weight *sw* allows managers to consider varying and possibly conflicting habitat needs of different species at different points in time. Although the weighting approach has been criticized for focusing on limited, key indicator species [*King et al.*, 2008], here the key-indicator species focus explicitly follows Refuge goals to manage for select migratory bird species. Further, the vegetation habitat suitability index can vary through time as invasive vegetation cover changes and the *WU* metric explicitly considers water availability and invasive vegetation as key wetland stressors.

2.3. Management Actions and Decision Variables

To improve wetland habitat for priority bird species, managers can adjust water levels in wetland units or remove invasive vegetation from units. Adjusting water levels requires deciding the flow rate [$Q_{t,i,j}$ (ha-m/month)] in a canal segment during time t (month) from a start location i (an index) to a destination location j (an alias of the index i). Additionally, the storage volume [$S_{t,w}$ defined previously], water depth [$WD_{t,w}$ (m)], and flooded area [$A_{t,w}$ (m^2)] in each time t at the subset of nodes w that are wetland units ($w \epsilon i$; storage is constrained to be zero at the remaining nodes that are simple junctions). Wetland unit storage, water depth, and flooded area decisions are readily related by observed depth-storage and area-storage volume relationships [$WD_{t,w} = wd_w(S_{t,w})$; $A_{t,w} = a_w(S_{t,w})$].

A second category, invasive wetland vegetation management actions, includes (i) vegetation removal by burning, herbicide application, grazing, and mowing in each time step t and wetland unit w ($RV_{t,w}$), and (ii) the invasive vegetation cover ($IV_{t,w}$) present in each wetland unit w at the end of time step t (both *RV* and *IV* are quantified as a percentage of the total wetland unit area). The complement of invasive vegetation cover (100 - *IV*) indicates cover by native vegetation or open water. Explicitly representing invasive vegetation cover allows the model to track this attribute in time, vegetation response to natural factors and removal efforts, and corresponding changes in habitat suitability for priority bird species.

2.4. Relating Management Actions and the Performance Metrics

We use habitat suitability curves and the weighted usable area method presented in Section 2.2 to relate decision variables representing water allocation and invasive vegetation removal actions to the *WU* metric. Habitat suitability curves are based on a literature review, historical data, controlled experiments, and expert opinion [*Hardy*, 2005]. Their use allows us to (i) separately and independently assess how water depth and invasive vegetation cover habitat attributes in wetland units meet the habitat needs of priority bird species, and (ii) tractably incorporate the relationship between management actions and *WU* metric in a non-linear systems optimization model.

Figure 2 shows how invasive vegetation (*Phragmites*) cover at the Refuge influences habitat suitability for one of the priority bird species, black-necked stilt (*Himantopus mexicanus*). Habitat suitability ranges from 1 (excellent) habitat quality when little *Phragmites* is present to 0 (poor) quality when *Phragmites* covers more than 10% of the total area of a wetland unit. While a small amount of *Phragmites* cover is desirable because the plant provides some nesting strata, hiding, and thermal cover, *Phragmites* cover greater than 10% is undesirable because black-necked stilt cannot enter dense *Phragmites* stands to feed or breed; also, *Phragmites* displaces native aquatic vegetation with higher wildlife values [*Olson*, 2007]. Refuge managers describe 10% *Phragmites* cover as a goal of invasive vegetation control efforts.

Mathematically, habitat suitability variables associated with the invasive vegetation cover and water depth attributes ($HV_{t,w,s}$ and $HW_{t,w,s}$ defined previously) are, respectively, functions (fv_s and fw_s) of the invasive vegetation cover and water depth (IV and $WD_{t,w}$, defined previously, where water depth is itself a function of storage [$S_{t,w}$]) at each time t, wetland unit w, and for each priority species s (Eqs. 2 and 3).

$$HV_{t,w,s} = fv_s\left(IV_{t,w}\right) \ , \quad \forall t, w, s \tag{2}$$

$$HW_{t,w,s} = fw_s\left[wd_{t,w}\left(S_{t,w}\right)\right] \ , \quad \forall t, w, s \tag{3}$$

Here, fv_s and fw_s are continuous and smooth non-linear functions to avoid numerical difficulties in the model solution such as shown in Figure 2. If habitat suitability includes threshold effects, then function curvature can be adjusted or a smooth and more sharply transitioning function substituted (e.g., see constraint on gate changes in the next section and supplementary material).

2.5. Constraints

Management actions and decision variables are subject to hydrological, vegetation, and management constraints (Eqs. 4-11). One set of hydrological constraints use a simple low order finite-difference approximation to require water mass balance at each time t and node i (Eq. 4) while Eqs. 5 and 6 place minimum and maximum limits on channel conveyance and storage in wetland units.

$$in_{t,i} + \sum_j lq_{j,i} \cdot Q_{t,j,i} - \sum_j Q_{t,i,j} - le_t \cdot a_{t,i}\left(S_{t,i}\right) = S_{t,i} - S_{t-1,i} \ , \quad \forall t, i \tag{4}$$

$$qm_{ij} \le Q_{t,i,j} \le qx_{ij} \ , \quad \forall t, i, j \tag{5}$$

$$sm_i \le S_{t,i} \le sx_i \ , \quad \forall t, i \tag{6}$$

Here, $in_{t,i}$ (ha-m/month) is the inflow during time period t at node i; $lq_{j,i}$ (unitless) is a loss coefficient in the channel from node j to node i; le_t (m) is the evaporation during time period t; $S_{t-1,i}$ (ha-m) is the storage in the previous time-step, $qm_{i,j}$ and $qx_{i,j}$ (each ha-m/month) are, respectively, the minimum and maximum flow capacities between nodes i and j during a time period; and sm_i and sx_i (each ha-m) are, respectively, the minimum and maximum water storage capacity at node i. Note, storage at time zero ($S_{0,\mathrm{i}}$) specifies a user-provided initial storage at node i. Also, setting sm and sx to zero defines a simple hydraulic junction with no storage and renders only the first three terms of mass balance constraint (Eq. 4) active. The remaining subset of nodes w represent wetland units, allow storage ($sx > 0$), and are where wetland performance is measured in Eq. 1.

Vegetation cover constraints dynamically track changes in invasive vegetation cover in each wetland unit w through time by requiring that invasive vegetation cover in each wetland unit at the end of time step t ($IV_{t,w}$) equal cover at the end of the prior time step ($IV_{t-1,w}$), minus invasive vegetation removed by managers ($RV_{t,w}$), and plus natural growth ($vr_{t,w}$) (all terms expressed as a percent of the wetland unit area) (Eq. 7).

$$IV_{t,w} = IV_{t-1,w} - RV_{t,w} + vr_{t,w} \ , \quad \forall t,w \qquad (7)$$

The natural invasive vegetation growth rate (vr) presently reflects the 10% annual areal expansion noted by experts and reported in prior *Phragmites* studies under various water level, flow duration, and nutrient conditions [*Hudon et al.*, 2005; *Kettenring et al.*, 2011; *Mozdzer and*

Zieman, 2010; *Saltonstall and Stevenson*, 2007]. In reality, hydrology [*Chambers et al.*, 2003; *Weisner and Strand*, 1996], mechanism of reproduction and spread [*Kettenring and Mock*, 2009], plant life stage, and other environmental factors [e.g., *Kettenring et al.*, 2011; *Kettenring et al.*, 2015; *Rickey and Anderson*, 2004] influence *Phragmites* growth and cover and are areas of ongoing research. As a first attempt to represent the influence of vegetation growth, we use a constant growth rate. As in Eq. 4, invasive vegetation cover at time zero ($IV_{0,w}$) specifies a user-provided initial invasive vegetation cover in wetland unit w (percent of wetland unit area).

Vegetation management constraints establish a financial operating budget to remove invasive vegetation, b ($), for the analysis period (Eq. 8) and set upper limits on invasive vegetation removal (Eq. 9). The upper limit is either the current invasive vegetation cover or a user specified limit, $vegm_t$ (percent of wetland unit area):

$$\sum_{t,w} RV_{t,w} \cdot ta_w \cdot uc_t \leq b \tag{8}$$

$$RV_{t,w} \leq IV_{t,w};\ RV_{t,w} \leq vegm_t, \quad \forall t, w \tag{9}$$

where ta_w (m^2) is the total area of wetland unit w, uc_t ($\$/m^2$) is the unit cost to remove invasive vegetation during time period t, and $RV_{t,w}$ and $IV_{t,w}$ are the removal percentage and invasive vegetation cover (defined previously). Unit costs in Eq. 8 reflect costs for labor, equipment operation, and materials that are proportional to the area controlled and vary temporally because managers mow, burn, and apply herbicides at different times in the year.

A water management constraint further limits the number of manual operations to open or close wetland unit gates in a time step (G_t) to no more than the total operations allowed by available Refuge staff time and personnel (ag_t) (Eq. 10).

$$G_t \leq ag_t \quad , \quad \forall t \tag{10}$$

Here, we use a smooth, sharply transitioning sigmoidal function presented in the Supplemental Material to calculate counts of manual operations to open and close wetland unit gates (G_t) from changes in hydrologic decision variables from one time step to the next. Manual operations are required when either (i) releases from a wetland unit increase or decrease, or (ii) deliveries to a wetland unit decrease. Increasing wetland unit deliveries do not require manipulating gates because gate settings at the prior time period can tolerate higher flow during the next time period.

A final set of constraints require the decision variables *S*, *Q*, *WD*, *IV*, *RV*, and *G* to be non-negative. Together, maximizing the objective function (Eq. 1) subject to constraints (Eqs. 2 – 10) comprises a non-linear optimization model.

2.6. Simulation Capabilities

Additional optional constraints set wetland unit storage values equal to prior observed or desired storage volumes ($ds_{t',w'}$) at specified times *t'* in specific wetland units *w'* (Eq. 11).

$$S_{t',w'} = ds_{t',w'} \quad , \quad \forall t' \in t, w' \in w \tag{11}$$

These constraints allow managers to simulate wetland performance under past observed hydrological conditions or to allocate pre-determined volumes of water to particular wetland units and achieve additional goals or constraints that are not already included in the model. Examples include requiring specific water depths in wetland units to provide recreation or hunting services (not already explicitly represented in the objective function) or drain and dry wetland units for maintenance or control for avian diseases like botulism.

2.7. Model Outputs

Key model outputs comprise reports, time series, and maps that show model recommended water allocations and vegetation control actions among wetland units and how actions affect the overall *WU* metric and *WU* in individual wetland units. Additional outputs include a composite habitat suitability [$HC_{t,w}$ (unitless; ranging from 0 to 1)] which is the expression in parenthesis in Eq. 1 and represents concurrent water depth, vegetation cover, and species prioritization suitability factors. Shadow value (Lagrange multiplier) results associated with water mass balance and financial budget constraints (Eqs. 4 and 8) further show how water availability and vegetation removal affect overall wetland performance. Comparing results across scenarios identifies the individual and combined effects on *WU* of water and vegetation system components.

3. Model Application

3.1. Study Area

We apply the systems model at the Bear River Migratory Bird Refuge, Utah, which lies at the terminus of the Bear River on the northeast corner of the Great Salt Lake (Figure 3). The Refuge covers 156.3 km^2 divided into 25 managed wetland units that are separated by dikes and supplied water through a network of canals controlled by gates and weirs. The Refuge is experiencing a *Phragmites* invasion and may also see reduced water inflows compared to recent years if Bear River water is transferred out of the basin to support urban growth on the Wasatch Front, Utah [*Anderson et al.*, 2004]. Thus, Refuge managers are very interested to learn how they can more efficiently use available water to enhance habitat for priority bird species and better coordinate their water and vegetation management efforts.

Currently, Refuge managers use the gates and weirs to fill wetland units in winter and spring and hold water at constant levels through the summer and early fall. However, this strategy can be difficult to implement in summer months because the Refuge holds a junior water right and more senior Bear River agricultural users have first priority under Utah water rights law to divert water to satisfy their own full, upstream, consumptive, summer irrigation uses before the Refuge can take any water [*Downard et al.*, 2014; *Kadlec and Adair*, 1994]. Simultaneously, Refuge managers expend considerable effort to control *Phragmites* with herbicides (usually glyphosate) followed by burning to remove dead *Phragmites* [*Olson*, 2007]. Since 2007, managers have prioritized control efforts in 9 wetland units with *Phragmites* cover greater than 10% (typically two units per year). Below, we present the input data and model results that we have developed in collaboration with Refuge managers since 2009. Input data comprise a base case analysis for the calendar year 2008. The calendar year also represents the Refuge's time horizon for planning annual water and vegetation management activities.

3.2. Input Data and Model Scenarios

The network comprises 3 inflow water sources (Bear River, Malad River and Box Elder creek), 25 wetland units, 70 junctions, 5 outlets, and canals (Figure 3). Inflow data for the Bear River was obtained from the United States Geological Survey station (10126000 Bear River near Corinne, UT). For the Malad River and Box Elder Creek, some flow data was obtained from nearby private property owners such as the Bear River Club (a duck hunting organization). In other cases, we correlated missing gauge records with Bear River flows at the Corinne station.

From the 20 priority bird species listed in the Refuge Habitat Management Plan [*Olson et al.*, 2004], we and the Refuge managers identified three priority bird species [black-necked stilt (*Himantopus mexicanus*), American avocet (*Recurvirostra americana*), and tundra swan (*Cygnus columbianus*)], their habitat requirements, and corresponding habitat suitability curves to include in the modeling. We selected these species because they need different shallow, medium, and deep water conditions (Figure 4) at different times of the year (Table 1) and because these needs encompass the needs of other priority bird species. For example, black-necked stilt are present at the Refuge between April and September and prefer shallow water depths between 0.15 and 0.25 m to feed. During the same time, up to 55% of the continental avocet population uses the Refuge to feed, nest, brood, rear hatchlings, and stop during migration before departing for other wintering grounds. Avocets feed deeper below the water surface (0.35 m - 0.45 m) and the large avocet population coupled with diverse feeding, resting, and breeding activities undertaken while at the Refuge mean managers assign this species a high priority species weight *sw*. In contrast, tundra swan use the Refuge as a staging area and migratory stopover during winter months, can tolerate shallow or medium depth waters, but prefer to feed and rest in water greater than 0.55 m [*Olson et al.*, 2004]. Each of the priority bird species has similar habitat needs for native vegetation as discussed in Section 2.4 (Figure 2).

We used Refuge staff observations of wetland unit water levels and our estimates of *Phragmites* cover at the beginning of 2008 to define the initial water and vegetation conditions in each wetland unit. Initial *Phragmites* cover was estimated between 0 and 6% by reducing classifications of readily available Landsat 30x30 m satellite imagery in 2008 by factors of 0.03 to 0.36. These factors where the amounts by which similar Landsat classifications for 2010 overestimated *Phragmites* cover in select wetland units compared to 2010 classifications from high-resolution (1x1 m) airborne remote sensed imagery [*Vanderlinder et al.*, 2014].

Remaining model input data were obtained from: (i) Western Regional Climate Center web page (monthly pan evaporation estimates from http://www.wrcc.dri.edu/); (ii) studies of the Refuge's water requirements [*Christiansen and Low*, 1970; *Kadlec and Adair*, 1994]; and (iii) management and field data provided by Refuge staff, including the Refuge operating budget, June to November operational window for removing *Phragmites*, observed water levels in wetland units, and water depth-storage-flood area profiles for wetland units derived from LiDAR.

We used the input data to define a base case scenario that simulated *WU* for the water levels that Refuge managers set in 2008 (Eq. 11), existing *Phragmites* removal budget of $180,000/year, *Phragmites* growth of 10% per year prorated over the April to November growing season, and only allowing water levels to change in four wetland units per month (current Refuge staffing limits; Eq. 11). Scenario 1 removed the simulation constraints (Eq. 11) and recommended water allocations and *Phragmites* removal that maximized *WU*. Scenario 2 further relaxed the gate management constraint (Eq. 10) to allow staff to change water levels as often as needed. Although numerous gate changes are not feasible with manual operation, such changes are possible if the Refuge installs a remote-operated and computer-controlled gate system. Scenario 3 also allowed numerous gate changes but set the initial *Phragmites* cover and growth rate parameters (IV_0 and vr in Eq. 7) to zero to show the effects of hydrological habitat components on wetland performance. Scenarios 4 and 5 increased the initial *Phragmites* cover IV_0 in Eq. 7 by factors of 2 and 3 over the initial cover estimates for 2008. Additional sensitivity runs further modified the inflow parameter in Eq. 4 to identify effects of water availability observed in dry (1992), intermediate (1996 and 2004 to 2011), and wet (1997) years.

The model was implemented using the General Algebraic Modeling System (GAMS) and solved using the non-linear CONOPT solver [*Rosenthal*, 2014]. We used Matlab to post-process and graphically display results. All input data, model code, and post-processing scripts are available at [https://github.com/alminagorta/Systems-model-in-Wetlands-to-Allocate-water-and-Manage-Plant-Spread.](https://github.com/alminagorta/Systems-model-in-Wetlands-to-Allocate-water-and-Manage-Plant-Spread)

3.3. Results

Comparing results from the prior management (base case) and the first optimized scenario show there are opportunities at the Refuge to increase twofold the available surface area that provides suitable hydrological and vegetation conditions for the three priority bird species (Table 3). To achieve this increase, the model recommends to more dynamically vary water levels in most wetland units (Figure 5, red lines). More dynamic management typically raises water levels during January, February, and March, gradually lowers levels through the spring and summer, and again raises levels in the early winter (units 1, 1A, 2A, 2D, 3A, 3B, 3F, 3G, 3H, 3I, 3J, 4A, 5A, 5D). These actions also maintain water in units 2D, 3A, 3B, 3C, 3D, 3G, 3H, and 3I through critical summer months and contrast with either the near-constant water depths managers maintained throughout 2008 or summer months when managers dried several units (Figure 5, blue bars).

With more dynamic management, composite habitat suitability (*HC*) for priority bird species is highest during winter (Figure 6) although some units maintain *HC* values greater than 0.5 all year. April through August are particularly critical months when most wetland units show poor conditions except for units 2C, 3D, and 4C. The model concentrates *Phragmites* removal in seven wetland units in June at the beginning of the window for removal operations to achieve or sustain excellent habitat suitability of vegetation cover for the duration of the year (Supplemental Material, Figures SM.2 and SM.3). Thus, temporal and spatial variations in *HC* are largely due to the water depth habitat component.

Shadow values (Lagrange multipliers) associated with water mass balance (Eq. 4) show that one additional ha-m of Bear River water will most increase wetland performance in the late summer months of July, August, and September (Table 2). In contrast, the shadow value associated with the financial budget constraint (Eq. 8) is low (Table 3).

Further scenario analysis shows that installing a system of automatic gates (i.e., staff can adjust water levels in wetland units as often as they need) improves wetland performance a further 15% in comparison to the first optimized scenario (Table 3). Optimizing absent *Phragmites* (Scenario 3) offers a further small increase in wetland performance compared to the automatic gates scenario. Here, habitat suitability for vegetation is always excellent, water depth is the sole factor that influences wetland performance, and the scenario emulates prior systems modeling studies that use only a flow-based ecological objective. In contrast, increasing initial *Phragmites* cover by factors of two or three over the cover values estimated for 2008 (Scenarios 4 and 5) decreases wetland performance compared to Scenario 3, increases the shadow value associated with the financial budget to pay for *Phragmites* removal, and alters the magnitudes and timings of water allocations in 15 of the 25 wetland units (Supplemental Material, Figure SM.4).

Further sensitivity analyses simultaneously vary the initial *Phragmites* cover and water availability and show three linkages among the system hydrological and vegetation components (Figure 7). First, there is a non-linear relationship between wetland performance and water availability regardless of the initial *Phragmites* cover. Second, runs with initial invasive vegetation cover at levels estimated for 2008 perform nearly identical to runs with zero *Phragmites* cover and growth except for the case of very low water availability. And third, as initial *Phragmites* cover and water availability increases, the difference in wetland performance with respect to the no *Phragmites* condition grows both absolutely and relatively.

4. Discussion

The model results suggest ways to better manage the linked hydrologic and vegetation components of the diked wetland system to improve habitat for priority bird species. The scenarios of optimized and past management show that there are opportunities to increase by two-fold the suitable wetland habitat area. This increase can be achieved by more dynamically managing water levels in the wetland units, controlling invasive vegetation early in the management window, and partially controlling *Phragmites* in a larger number of wetland units than the two units per year where Refuge staff typically undertake full control. The scenario that relaxes restrictions on gate operations further suggests operational flexibility to manage water can improve wetland performance and Refuge managers should investigate options to install an automatic system to control gates and weirs throughout the Refuge. And while prior work has also identified the need for early detection and rapid response to control invasive vegetation [*NISC*, 2003], here our model results suggest how to spatially configure responses among wetland units and coordinate response with other habitat factors like hydrologic conditions.

In scenario one with optimized management and scenario two with unlimited gate changes, the low shadow values associated with the vegetation removal budget constraint and small increase in wetland performance when no *Phragmites* was present initially suggest that there may be little value to explicitly represent vegetation in the systems model. In other words, one could adequately define ecological objectives from only flow variables as in prior systems modeling studies [*Cardwell et al.*, 1996; *Higgins et al.*, 2011; *Loucks*, 2006; *Steinschneider et al.*, 2013; *Stralberg et al.*, 2009; *Szemis et al.*, 2014]. In these scenarios, *Phragmites* cover had a seemingly small influence because cover was low relative to managers' target of 10% cover and habitat suitability of vegetation stayed at or close to a value of 1 (excellent). Also, there was sufficient budget to remove and maintain low *Phragmites* cover throughout the one-year planning horizon.

However, subsequent scenarios and sensitivity runs suggest that much higher levels of initial *Phragmites* cover will noticeably decrease wetland performance (Figure 7). Thus, we can interpret the scenario with no *Phragmites* cover or growth as an upper bound on wetland performance. And systems models that only consider the hydrologic habitat needs of priority species may overestimate performance and mischaracterize the relationship between performance and water availability when those species have concurrent habitat needs for wetland plant vegetation or needs are driven by additional abiotic or biotic factors such as vegetation cover.

The scenario and sensitivity results in Figure 7 suggest three further related strategies to manage water and vegetation at the Refuge. First, maintain water availability above the existing Refuge water right of 52,000 ha-m/year (Figure 7; red vertical line) to prevent a sharp decline in wetland performance. Second, apply additional available water in July, August, and September when shadow values associated with the water mass balance constraint are largest (Table 2). And third, the largest increases in wetland performance per unit of available water or per dollar of budget available to remove *Phragmites* occur when *Phragmites* cover is near managers' 10% cover target (Figure 7 and Table 3). Thus, Refuge managers should be concerned about upstream water abstractions that reduce available water and should also focus *Phragmites* control in wetland units where removal can maintain or return vegetation cover to conditions that are suitable for priority birds.

Currently, the model assumes linear growth of *Phragmites* in wetland units over time and no interaction with water level. *Phragmites* growth and expansion is also influenced by mechanism of plant reproduction, salinity, and anthropogenic disturbance, and future work should better incorporate these potential effects. Remotely sensed images and controlled field experiments can provide the empirical data to further specify these hydrological-plant response relationships and mathematically represent them in the systems model.

The model calculates the wetland performance metric by multiplying wetted area and habitat suitability indices for water depth and invasive vegetation cover. This multiplication reflects priority bird species concurrent needs for suitable hydrologic and vegetation habitat conditions at the same time and in the same wetland unit. Wetland performance could alternatively be estimated as a geometric mean that implies compensatory relationships between individual suitability indices or as a minimum composite suitability [*Waddle*, 2001]. Further study can help identify how these different methods to aggregate suitability indices influence overall wetland performance, interactions among system components, and recommended management actions.

There will likely also be benefit to include additional habitat attributes and suitability variables in the model besides the hydrologic and vegetation components we consider here. With available input data, we could extend the model to include variables and suitability indexes for salinity or nutrient levels, substrate cover, temperature, and/or native vegetation. Including these abiotic and biotic factors and components will require field data and a more explicit description of the underlying ecology to describe current conditions, empirically relate variable values to habitat suitability, and combine suitability indexes.

Lastly, Refuge managers' participation in the work offered several benefits, including to: (i) ensure the model addresses a real, existent problem, (ii) populate the model with current data, (iii) help validate and interpret results, and (iv) focus recommendations on actions managers can implement. For example, after we presented a first set of model results that extensively varied water levels in wetland units from month-to-month, Refuge managers said they liked the results but could not implement them because of limited staff and time to adjust gates and weirs. Thus, we added Eq. 10 to restrict gate operations and re-interpreted results from that scenario to indicate the potential benefits of an automatic water control system. In continuing work, managers want to build a more user-friendly model interface, expand the number of priority species, include salinity and long-term water shortages, and use the model in their annual planning of water and vegetation management.

5. Conclusions

In arid regions, scarce water and invasive vegetation are common problems that affect wetland management for ecosystem functions and services. While prior systems modeling efforts have focused on water management to improve flow-based habitat objectives, here we consider water allocation and *Phragmites* removal to improve the hydrologic and vegetation characteristics of habitat for priority wetland bird species. We formulate a composite weighted usable area for wetlands (*WU*) objective that represents the wetted wetland surface area that provides suitable water depth and vegetation cover conditions for priority bird species. Maximization of *WU* is subject to constraints on water balance, hydraulic infrastructure capacity, invasive vegetation growth and control, and a limited financial budget to control vegetation. We apply the model at the Bear River Migratory Bird Refuge, which is the largest wetland complex on the Great Salt Lake, Utah.

Model results suggest that Refuge managers can double the area of suitable wetland habitat by more dynamically changing water levels, removing invasive vegetation early in the growing season, and partially controlling *Phragmites* in a larger number of wetland units. Also that managers can further improve wetland performance by more flexibly operating water control structures such as by installing an automatic gate control system. And additionally that at low invasive vegetation cover such as reflecting estimates for *Phragmites* at the Refuge in 2008, there may be little benefit to include the vegetation component within the model. However, we observe pronounced effects on wetland performance should there be higher invasive vegetation cover near or above the Refuge target of 10% *Phragmites* cover. At these higher vegetation disturbance levels, systems models that look at only the hydrologic habitat needs of priority species may overestimate performance and mischaracterize the relationship between performance and water availability.

Jointly considering wetland hydrology and vegetation further emphasizes that managers should protect the Refuge water right; additional water can achieve the most habitat benefit in the months of July, August, and September; and managers should focus *Phragmites* removal in wetland units where they can maintain or return habitat to excellent conditions. Future work should identify dynamic vegetation responses to water levels through time, extend the wetland performance metric to consider additional abiotic and biotic factors that affect bird habitat, and consider alternative ways to mathematically aggregate habitat suitability indices. Together, the work links hydrologic and vegetation components of a diked wetland system and recommends coordinated water and vegetation management to improve habitat for priority species.

Acknowledgments

This research was founded by the Utah Water Research Laboratory and Utah Mineral Lease funds. We thank the Bear River Migratory Bird Refuge managers and wildlife biologists, particularly Bridget Olson, Bob Barrett, Sharon Vaughn, Katie McVey and Howard Browers for their participation, feedback, and support. Model input data, source code, and post-processing scripts are available under a BSD 3-Clause license at https://github.com/alminagorta/Systems-model-in-Wetlands-to-Allocate-water-and-Manage-Plant-Spread.

Notation

The following symbols are used in this paper:

$A_{t,w}$ = Flood area in time *t* at each wetland unit *w*, m^2.

ag_t = Number of wetland units whose gates or weirs can be manipulated (opened or closed) in time *t*.

b = Total budget per year to reduce invasive vegetation, \$/year.

$ds_{t,w}$ = Specified (simulated) water volume in time *t* for wetland unit *w*, ha-m.

fw_s = Function that relates habitat suitability and water depth for priority species *s*.

fv_s = Function that relates habitat suitability and invasive cover vegetation for priority species *s*.

G_t = Number of manual operations required to open or close wetland unit gates in a time *t*.

H = Habitat suitability indices.

$HC_{t,w}$ = Composite habitat suitability index for hydrologic and ecologic conditions in time t at wetland unit w, unitless.

$HV_{t,w,s}$ = Habitat suitability index related with invasive vegetation cover in time t at wetland unit w for priority species s, unitless.

$HW_{t,w,s}$ = Habitat suitability index related with water depth in time t at wetland unit w for priority species s, unitless.

$in_{t,i}$ = Inflow in time t at node i, ha-m/month.

$IV_{t,w}$ = Invasive vegetation cover in time t in wetland unit w, %.

le_{t} = Rate of evaporation loss during time period t , m.

$lq_{j,i}$ = Loss coefficient from node j to node i, unitless.

$Q_{t,i,j}$ = Flow rate from node i to node j during time period t, ha-m/month.

$qm_{i,j}$ = Minimum required flow from node i to node j during time period t, ha-m/month.

$qx_{i,j}$ = Maximum allowable flow from node i to node j during time period t, ha-m/month.

$RV_{t,w}$ = Removed invasive vegetation cover in time t at wetland unit w, %.

$S_{t,w}$ = Storage in time t and wetland unit w, ha-m.

sm_i = Minimum storage in node i, ha-m

sx_i = Maximum storage in node i, ha-m

$sw_{t,s}$ = Weight in time t for priority species s, unitless.

ta_w = Area of wetland unit w, m^2.

uc_{t} = Unit cost of removing invasive vegetation in time t, \$/month.

$vegm_t$ = Upper limit on invasive vegetation removed in time *t*, %.

$vr_{t,w}$ = Natural vegetation response in time period *t* and wetland unit *w*, %.

vs_t = Invasive vegetation spreads at time period *t*, %.

$WD_{t,w}$ = Water depth at time *t* in wetland unit *w*, m.

$WU_{t,w}$ = Weighted usable area wetland in time *t* and wetland unit *w*, m^2.

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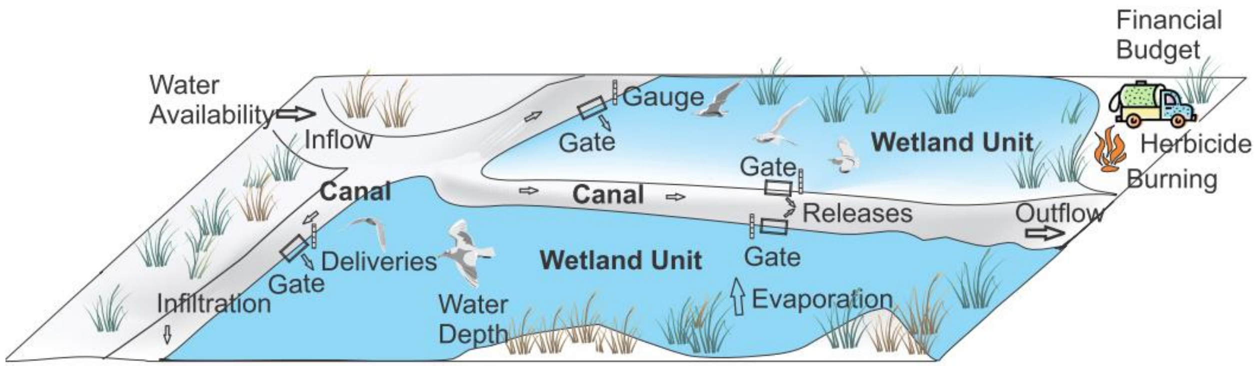

Figure 1. Major hydrological and vegetation components of the systems model for diked wetlands at the Refuge.

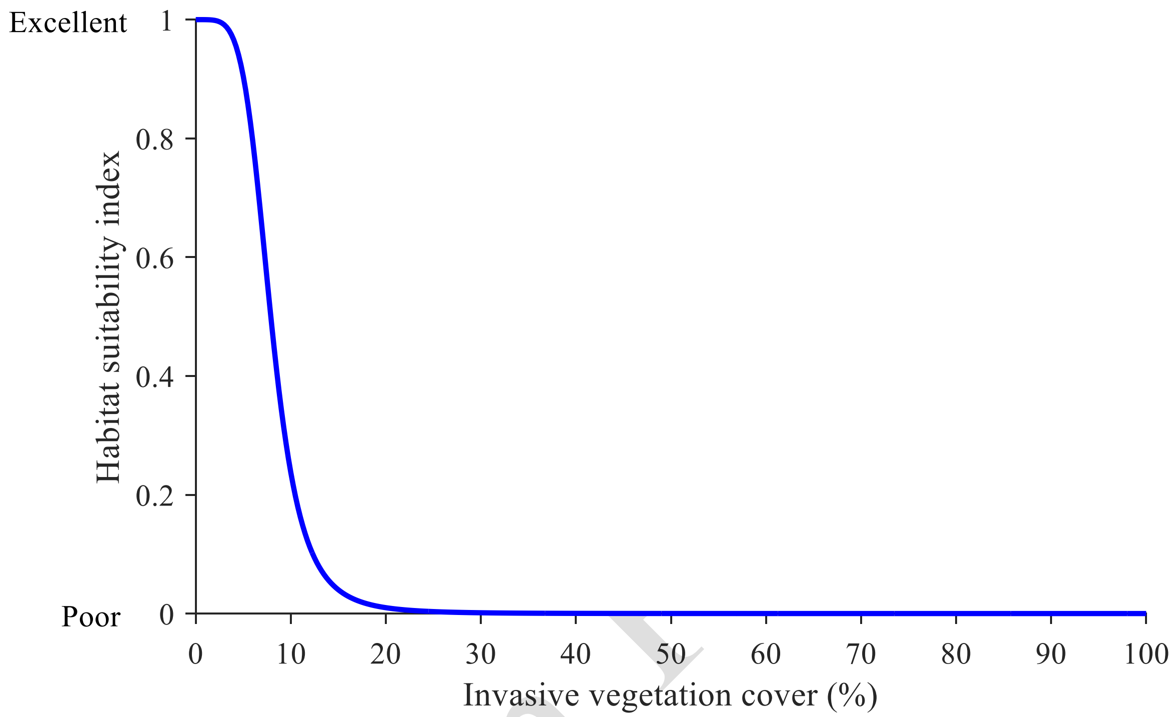

Figure 2. Example habitat suitability index for invasive vegetation cover (*Phragmites*).

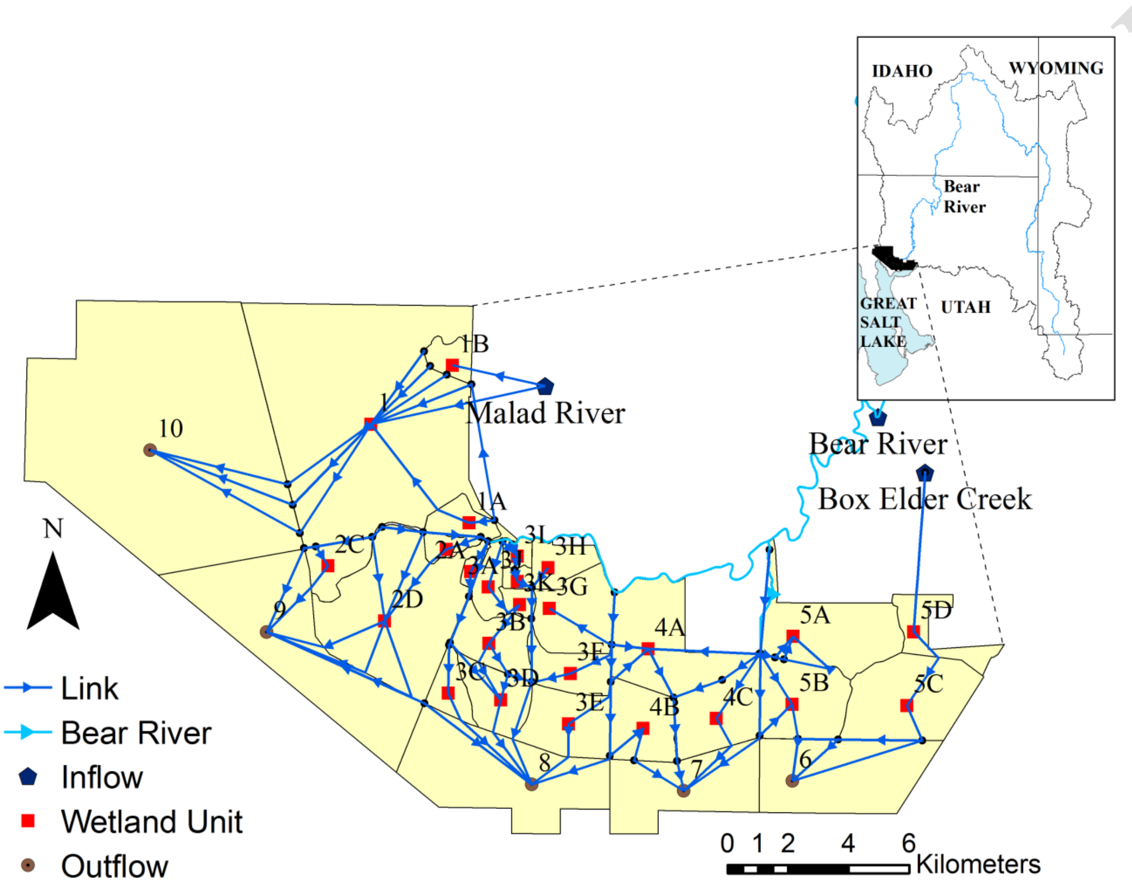

Figure 3. Bear River basin and the Bear River Migratory Bird Refuge with schematic of water inflow locations, 25 actively managed wetland units (units 1A to 5D), conveyance links, and outflows (units 6 to 10).

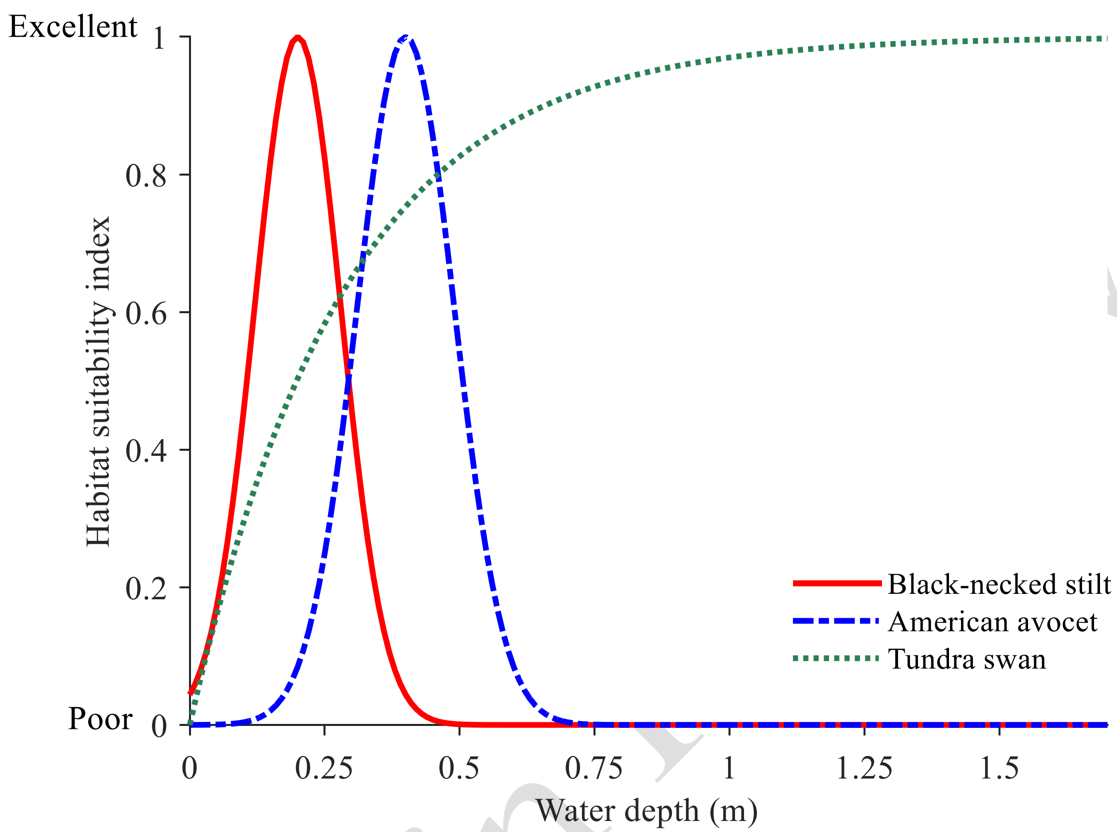

Figure 4. Habitat suitability of water depth in wetland units for three priority bird species at the Refuge.

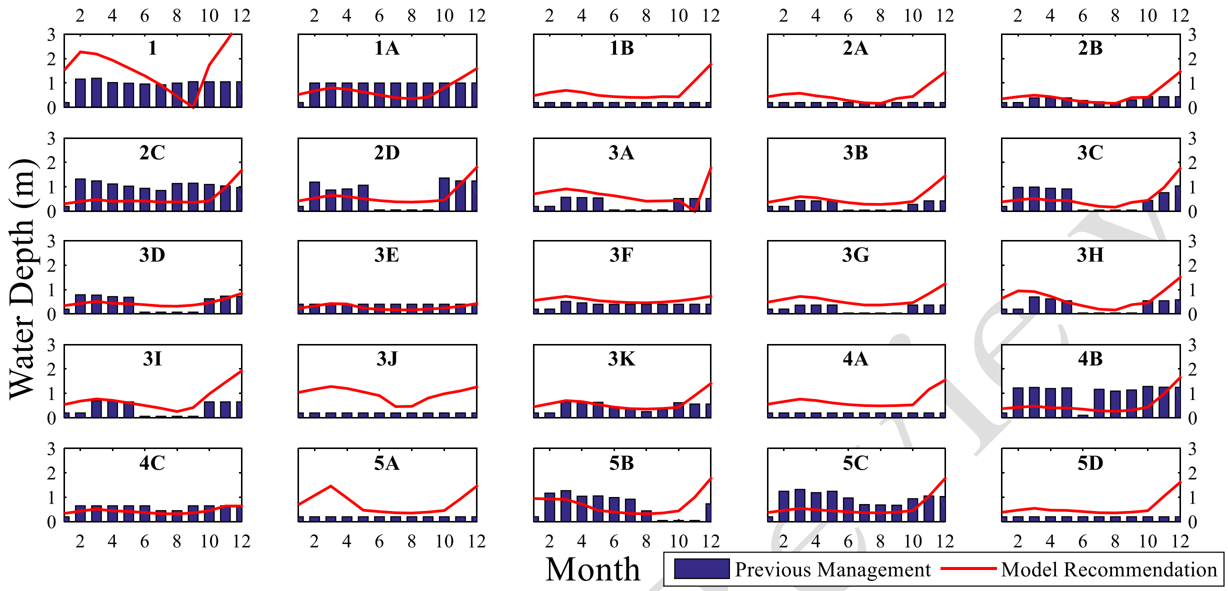

Figure 5. Comparison of model recommended (optimized, red line) and previous management (simulated, blue bars) water allocations by month and wetland unit during 2008.

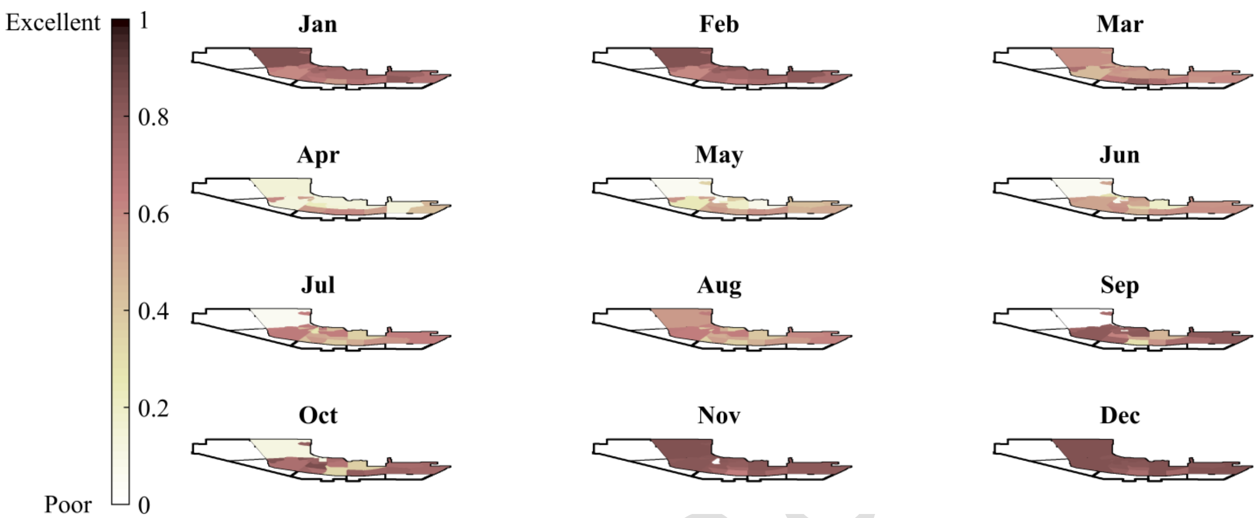

Figure 6. Spatial and temporal distribution of composite habitat suitability index *(HC)* for optimized case in 2008. Dark shading denotes areas with water depths and vegetation cover more suitable for the three priority bird species.

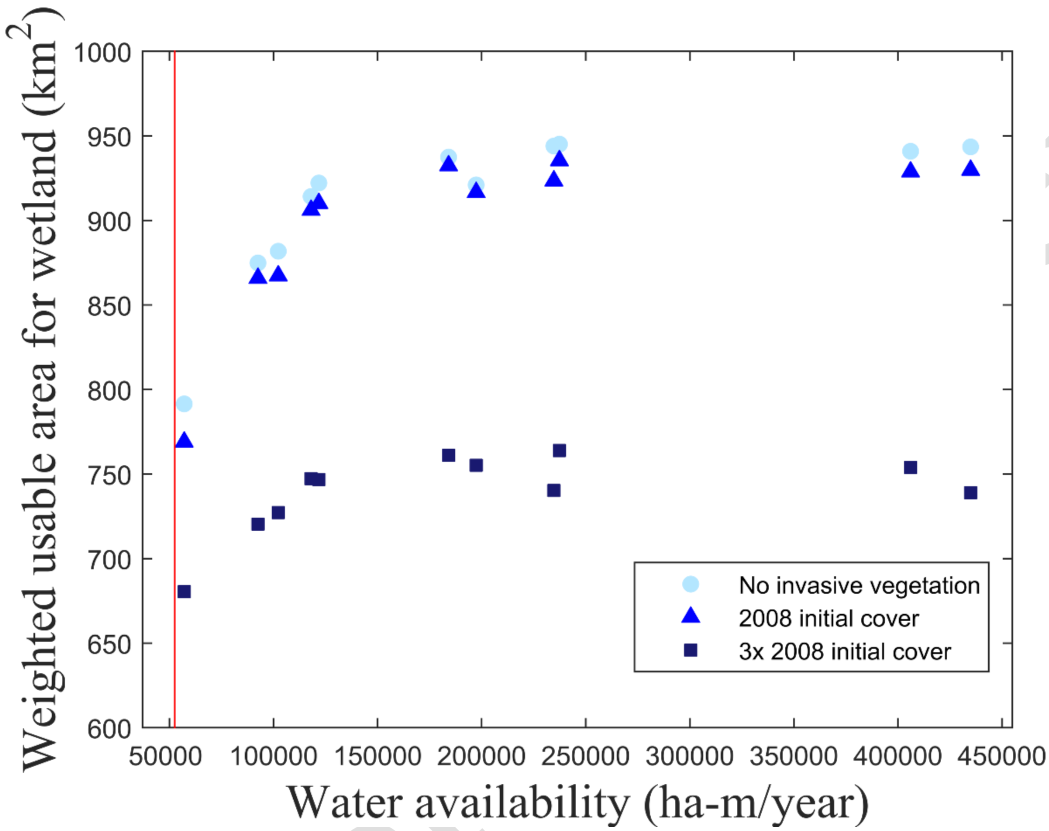

Figure 7. Weighted usable area for wetlands (y-axis) as a function of water availability (x-axis) and initial invasive vegetation cover (traces). The red vertical line shows the Refuge's annual water right.

Table 1. Water Depth Preferences and Weighting Parameters for Priority Birds Species.

Species	Water Depth Preferences	Weight [0 (not desired) to 1 (desired)]											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Black-necked stilt	Shallow	0.1	0.1	0.1	0.8	0.8	0.8	0.6	0.6	0.25	0.1	0.1	0.1
American avocet	Medium	0.1	0.1	0.6	1	1	1	1	1	1	0.6	0.1	0.1
Tundra swan	Deep	1	1	1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	1	1

Table 2. Increase in Weighted Usable Area for Wetlands per Additional Unit of Water in Scenario 1 of Optimized Management

Month	Shadow Value of Water Mass Balance Constraint (m^2/ha-m)
Jan	6,495
Feb	1,461
Mar	0
Apr	0
May	0
Jun	0
Jul	72,720
Aug	41,360
Sep	20,491
Oct	0
Nov	1,062
Dec	64

Table 3. Model Scenarios and Results.

	Scenario	Inputs		Results	
		Gate Changes per Month	Initial Invasive Vegetation Cover (fraction of 2008)	Weighted Usable Area for Wetlands (km^2/year)	Shadow Value of Budget Constraint (m^2/$)
	Previous Management (Base Case)	4	1	386	3.2
1	Model Recommendation	4	1	786	8.5
2	Automatic Gates	unlimited	1	906	9.1
3	No Invasive Vegetation or Growth	unlimited	0	914	0
4	Increased Invasive Vegetation	unlimited	2	809	251.6
5	Increased Invasive Vegetation	unlimited	3	747	146.8