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

H31I-1234

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Abstract

A systems model was developed to recommend water allocations and vegetation control actions among diked wetland units to improve wetland habitat for target bird species. Model recommendations are subject to constraints such as water availability, spatial connectivity of wetland units, hydraulic infrastructure capacities, vegetation growth, responses to management activities, plus financial and time resources available to manage water and invasive vegetation. We apply the model at the Bear River Migratory Bird Refuge, Utah. Results show that there are opportunities to increase by almost two-fold the hydro-ecological performance of wetland habitat by water allocation among wetland units and control of invasive vegetation such as *Phragmites australis* (common reed).

Background

- Water shortages, wetland drainage, agricultural and sub/urban land use, and invasive vegetation have degraded wetland ecosystems (Fig. 1). Thus, there is a need to assess management options to improve wetland habitat.
- Management of wetlands includes the manipulation of water levels to create a diversity of wetland habitats and improve habitat for water birds (Smith, Euliss et al. 2008).
- Wetland management also involves control of invasive vegetation such as *Phragmites* (Fig. 2). Excessive spread of invasive vegetation can reduce plant species diversity and limit resting habitat and food availability for birds (Zedler and Kercher 2004).
- Water allocation and vegetation management actions require resources that in many cases are limited. In these instances, wetland managers need tools to help them decide where to allocate water and control vegetation to improve the ecological performance of a wetland ecosystem.

Fig. 1. Scarcity of water in wetlands

Fig. 2. Invasive vegetation in wetlands

Research Objective

We developed and applied a system model that recommends water allocations among wetland units and vegetation management actions to improve the ecological performance of a wetland ecosystem.

Systems Model

- The model was developed for wetland units (w) where managers can control water allocation and invasive vegetation in each unit (Fig. 3).
- Managers control water levels through canals, gates, weirs, and other hydrologic infrastructure. Water allocations are affected by water availability, conveyance network, canal capacities, evaporation rates, and operation of gates.
- Managers control invasive vegetation cover using herbicide and burning. The effectiveness of invasive vegetation control is influenced by the natural growth of invasive vegetation and the available financial budget to reduce invasive vegetation.
- Controlling water levels and vegetation allows managers to create habitat that supports a diversity of wetland bird species (s) and plant community types that mimic a well-functioning freshwater ecosystem with multiple birding, hunting, and other wetland services.

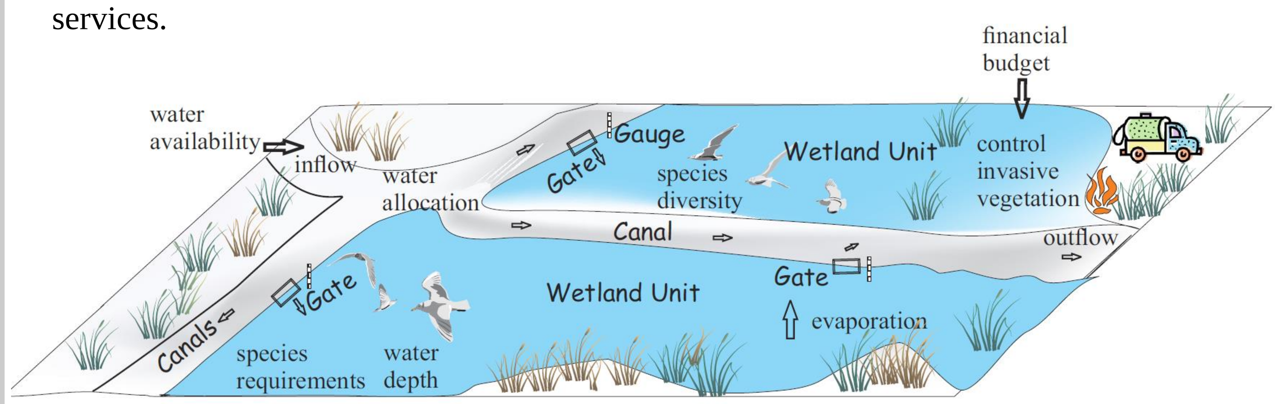

Fig. 3. Major components of the systems model for diked wetlands

Model Formulation

The model identifies potential wetland management actions to maximize wildlife habitat while simultaneously satisfying hydrological, ecological, and management constraints. We formulated the model in six phases (Fig. 4).

Phase	Model Components	
1.Wetland management purposes	➢Maximize wildlife habitat	
2.Performance metrics	➢Habitat suitability index (*H*) ➢Weighted usable area for wetlands (*WU*)	
3.Decision variables	➢Water depth (*WD*)	➢Storage (*S*) ➢Flood area (*A*) ➢Flow rate (*Q*)
	➢Invasive vegetation coverage (*IV*)	➢Vegetation removal (*RV*)
4.Relationship between decision variables and performance metrics	➢Habitat suitability related to water depth (*HW*) ➢Habitat suitability related to invasive vegetation (*HV*)	
5.Constraints	➢Water availability (*in*) ➢Budget to control invasive vegetation (*b*) ➢Gate operation (*ag*) ➢Species requirements (*sw*)	
6.Formulate Optimization Model	➢Identify values for water depth and invasive vegetation cover that maximize the weighed usable area while satisfying all constraints	

Fig. 4. Model phases

Wetland habitat performance

It is quantified using 2 performance metrics:

1. Habitat suitability index: 0 to 1, from poor to excellent habitat quality (Fig. 5).
2. The weighted usable area for wetlands represents the available surface area that provides suitable hydrological and ecological conditions for priority bird species.

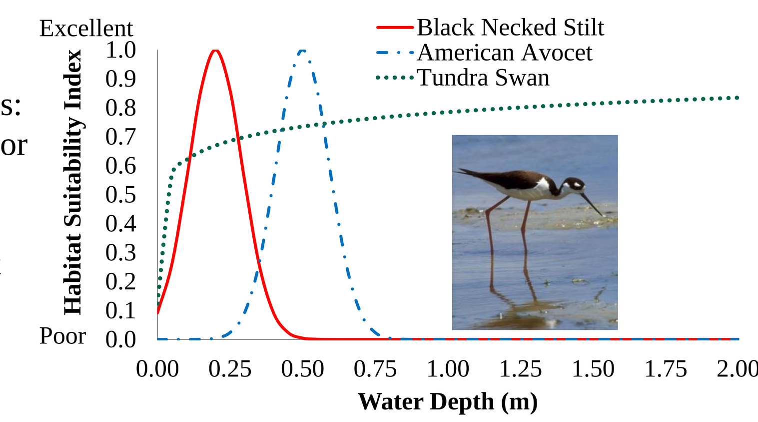

Fig. 5. Habitat suitability for 3 priority bird species

Objective Function

Maximizes the sum of the weighted usable area (*WU*) considering two main terms: (i) the combination of individual habitat suitability indices (*HW, HV*), and weighting parameter (*sw*) and (ii) the flooded area (*A*), which is a function of the variable storage (*S*).

$$Max.WU = \sum_{t,i}\left(\left(\frac{\sum_s HW_{t,i,s} * HV_{t,i} * sw_{t,s}}{\sum_s sw_{t,s}}\right) * A_{t,i}(S_{t,i})\right)$$

Subject to :

Hydrological Constraints

Mass balance equation at each network node *i*

$$in_{t,i} + \sum_j Q_{t,j,i} * lq_{j,i} - \sum_j Q_{t,i,j}$$
$$-A_{t,i}(S_{t,i}) * le_t = S_{t,i} - S_{t-1,i}, \quad \forall t,i$$

Ecological Constraints

Invasive vegetation reduction

$$IV_{t,w} = IV_{t-1,w} - RV_{t,w} + vr_t, \quad \forall t,w$$

Management Constraints

Limited budget to control invasive vegetation

$$\sum_{t,w} RV_{t,w} * ta_w * uc_t \leq b$$

Limited gate management operation

$$f(x) = \frac{G_c - G_d}{2} * \left[\frac{\tan^{-1}\left(\frac{(x-x_o)}{k}\right)}{\pi/2} + 1\right] + G_d$$

$$G^{(+)} = f(x)\,;\ G^{(-)} = f(-x)\,;$$
$$G_{t,w} = G^{(+)} + G^{(-)}, \forall t,w; \sum_w G_{t,w} \leq ag_t, \forall t$$

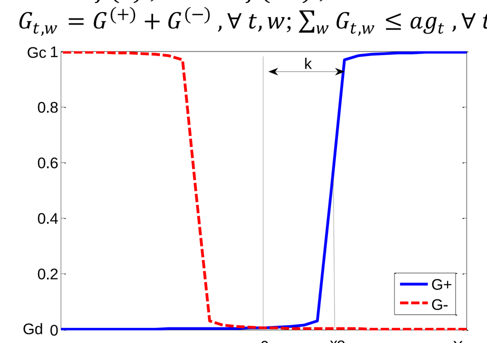

Fig. 7. Gate operation function

Simulation Capabilities

$$S_{t,w} = ds_{t',w'}, \forall t,w$$

Fig. 6. Gate operation and invasive vegetation control

Inputs	Modeling Tools	Outputs
Hydrological • Water availability • Network conveyance • Evaporation loss • Storage, area, and water depth relationships for wetland unit • Channel capacity **Ecological** • Initial vegetation coverage • Species habitat requirements • Species weights **Management** • Unit cost of removing invasive vegetation • Total budget to manage vegetation • Gate operation available	**Hydro Platform** • Manages inputs and displays network **GAMS** • Optimization software **MATLAB** • Output visualization	• Available surface area that provides suitable conditions for priority bird species • Recommended : o Water allocations to wetland units o Reduction of invasive vegetation o Allocation of financial budget to reduce invasive vegetation • Simulated water allocations • Quantify how changes in water availability, vegetation response, financial budgets, gate operation affect wetland performance

Fig. 8. Model inputs and outputs

Model Application

- We apply the model at the Bear River Migratory Bird Refuge (The Refuge), Utah. The Refuge is the largest wetland complex on the Great Salt Lake and an important stopping and resting area for migratory birds on the North American Pacific and Central Flyway (Fig. 9).
- The Refuge covers 118.4 km² and includes 25 wetland units maintained through a series of canals, gates, and dikes.
- Refuge managers participated throughout this study from identifying the problem, collecting data, through interpreting results.

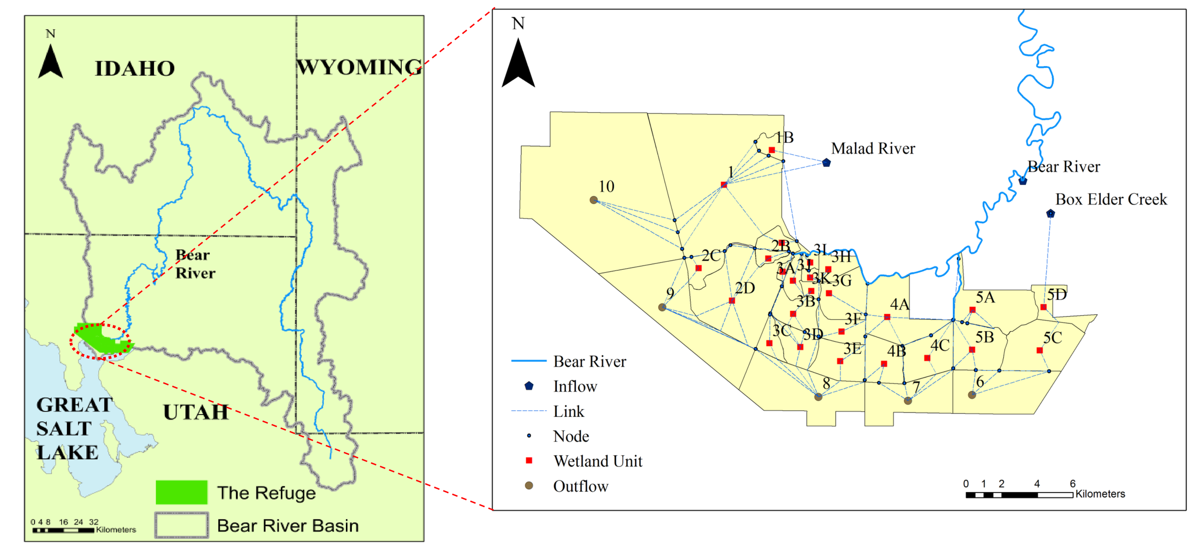

Fig. 9. Location of the Bear River Migratory Bird Refuge and its conveyance network

Results

- We ran the model for a base case (2008 hydrologic conditions) and seven scenarios.
- Comparison between the base case scenario of optimized management and past management activities show that there are opportunities to increase by almost two-fold the suitable wetland habitat area.
- Results of seven scenarios suggest that the performance of wetland habitat is more affected by variables related with vegetation responses, limited gate operation, and water availability rather than financial budget (Table 1).
- The model recommends water allocations and management of invasive vegetation to improve hydro-ecological performance (Fig. 10).

Table 1. Model results for changes in water availability, budget, vegetation response, and gate management scenarios.

	Scenario	Inputs: Water Availability (year)	Inputs: Budget ($1000/year)	Result: WU (km²/year)
	Base case	2008	180	571
	Simulation	2008	180	295
1	Dry condition	1992	180	468
2	Wet condition	1997	180	690
3	Increase budget by 50%	2008	270	583
4	Decrease budget by 50%	2008	90	563
5	Increase vegetation response 15% per year	2008	180	470
6	Increase vegetation response 50% per year	2008	180	317
7	Limiting gate management operation	2008	180	403

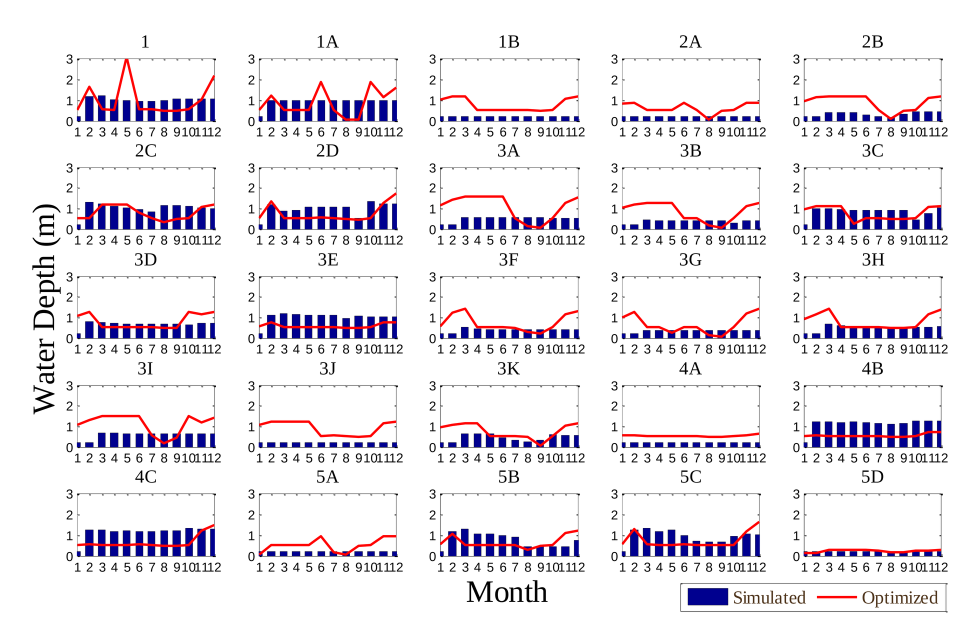

Fig. 10. Comparison of model recommended (optimized, red line) and historical (simulated, blue bars) water allocations during 2008 in each wetland unit.

More Results

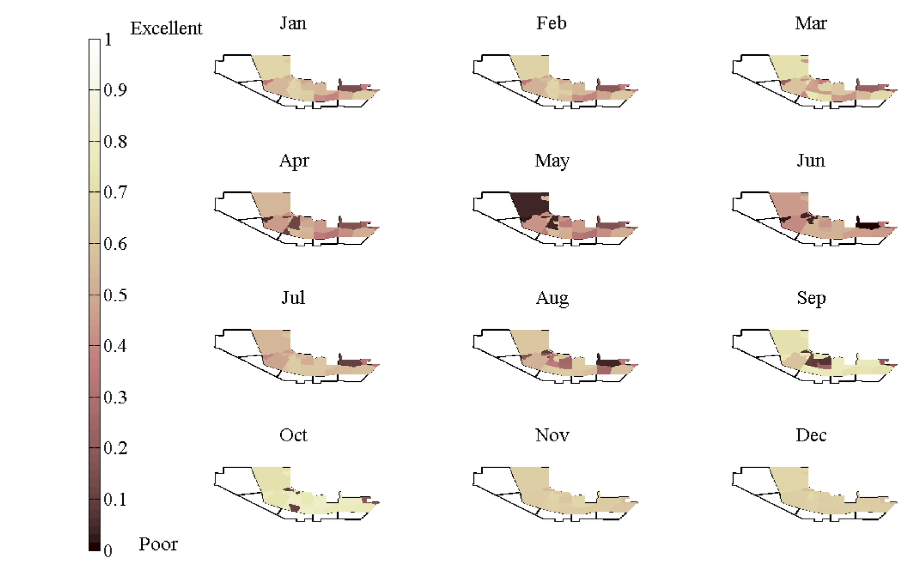

Figure 11. Spatial and temporal distribution of combined habitat suitability index for optimized condition in 2008. Dark shading denotes areas less suitable for priority species.

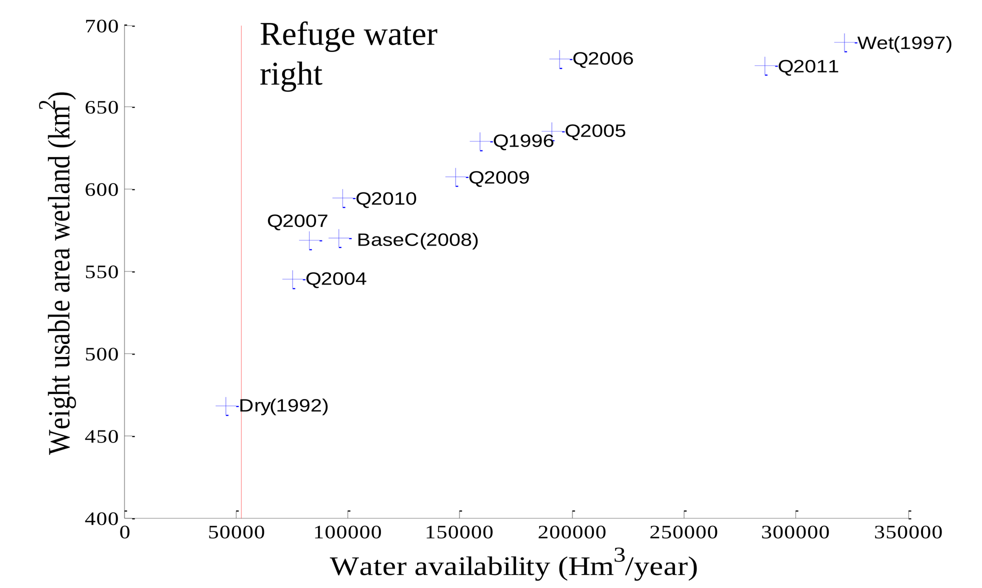

Figure 12. Relationship between water availability and Weight Usable Area for Wetlands indicator. Data points represent model scenarios including dry, base case, wet conditions, and annual discharges from 2004 to 2011 (Q2004 to Q2011).

The model shows that water availability below the Refuge's existing water right critically drops wetland performance. Thus, Refuge managers should be concerned about new upstream water abstractions that reduce available water.

Conclusions

- The optimization model identifies water depths and reduction of invasive vegetation coverage with the objective to maximize the area with suitable hydrological and ecological conditions for priority bird species while simultaneously satisfying constraints related with water availability, spatial connectivity, hydraulic capacities, vegetation responses, and financial resources.
- Refuge managers should continue controlling invasive vegetation, protecting the Refuge's water right and allocating water according to model recommendations to reach desired wetland management goals.

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