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Systems Optimization Models to Improve Water Management and Environmental Decision Making

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SYSTEMS OPTIMIZATION MODELS TO IMPROVE WATER MANAGEMENT AND ENVIRONMENTAL DECISION MAKING

by

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ABSTRACT

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Utah State University, 2015

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System models have been used to improve water management and environmental decision making. In spite of the many existing mathematical models and tools that attempt to improve environmental decision making, few efforts have been made to identify how scarce resources (e.g., water, budget) can be more efficiently allocated to improve the environmental and ecological performance of different ecosystems (e.g., wetland habitat). This dissertation presents a set of management tools to improve the environmental and ecological performance. These tools are described in three studies. First, a simple optimization model is developed to help regulators and watershed managers determine cost-effective best management practices (BMPs) to reduce phosphorus load at the Echo Reservoir Watershed, Utah. The model minimizes the costs of BMP implementation to achieve a specified phosphorus load reduction target. Second, a novel approach is developed to quantify wetland habitat performance. This performance metric is embedded in a new optimization model to recommend water allocations and invasive vegetation control in wetlands. Model recommendations are subject to

constraints such as water availability, spatial connectivity of wetland, hydraulic infrastructure capacities, vegetation growth and responses to management, plus financial and time resources available to allocate water and invasive vegetation control. Third, an agent-based model is developed to simulate the spread of the invasive *Phragmites australis* (common reed), one of the most successful invasive plant species in wetlands. Results of the agent-based model are embedded into an optimization model (developed in the second study) to recommend invasive vegetation control actions. The second and third studies were applied at the Bear River Migratory Bird Refuge, which is the largest wetland complex on the Great Salt Lake, Utah. These three studies provide a set of decision-support tools that recommend: (1) BMPs to reduce phosphorus loading in a watershed, (2) management strategies to improve wetland bird habitat, and (3) control strategies to minimize invasive *Phragmites* spread. Together, these models provide important insights and recommendations for managers to make informed decisions to manage excess nutrients in water bodies as well as to improve wetland management.

(145 pages)

PUBLIC ABSTRACT

Systems Optimization Models to Improve Water Management and Environmental Decision Making

Omar Alminagorta Cabezas

The degradation of water quality and wetlands is one of the most challenging environmental problems around the world. In spite of the magnitude of these environmental problems, few efforts identify how scarce resources (e.g., water, budget) can be more efficiently used to solve these problems. This dissertation presents a set of tools to help solve environmental problems related to excess phosphorus levels in water bodies and wetland degradation caused by water shortages and invasive vegetation. These tools are presented in three studies. The first study presents a simple optimization model that identifies the cost-effective combination of management practices to reduce excess of phosphorus in water bodies. The second study develops a nonlinear optimization model that recommends water allocation and invasive plant management to improve wetland bird habitat. And the third study develops a novel approach to provide strategies to control invasive vegetation. These studies were applied to real-case problems to reduce excess nutrients at the Echo Reservoir in Utah and improve wetland management at the Bear River Migratory Bird Refuge, one of the most important wetlands on the Great Salt Lake in Utah. Stakeholders and decision-makers participated in the development of the tools and examination of results. Results provide recommendations and insights for water and environmental managers to make informed decisions to improve water quality and wetland management.

To my parents, Eladio and Julia

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CHAPTER 1

INTRODUCTION

Water and environmental decision makers seek efficient ways to manage their scarce resources (e.g., water, budget). Typically, decision makers apply different model approaches, including systems optimization models, to maximize economic performance or minimize costs subject to different constraints (e.g., physical, management). These non-ecological objectives can include water volume, cost [*Draper et al.*, 2003], economic net benefits [*Harou et al.*, 2009], social equity, or proximity to a target. When considered environmental and ecological aspects typically are included as constraints such as satisfying a minimum in-stream flow value. A small but growing literature [*Cardwell et al.*, 1996; *Higgins et al.*, 2011] is moving beyond constraint methods to include one or multiple environmental objectives in system models. Important work remains to quantify environmental performance metrics for ecosystems and include those performance metrics in models that can recommend management actions to improve environmental and ecological performance. This dissertation develops a set of tools to recommend management of scarce resources (e.g., water, budget) to improve the environmental decision making, particularly related to reduce excess of nutrients in water bodies, quantify ecological performance in wetlands and improve wetland management. These tools are applied in the Echo Reservoir Watershed, Utah and the Bear River Migratory Bird Refuge, Utah.

Echo Reservoir, located on the Weber River, is affected by high concentrations of total phosphorus that negatively impacts aquatic habitat and water supplies for downstream urban and agricultural users. State regulators of the Utah Department of

Environmental Quality (UDEQ) require implementation of best management practices (BMPs) such as fence streams or grass filter strips to reduce phosphorus loading. However, implementation of BMPs is a challenging task for decision makers since they must consider multiple factors (e.g., site, cost, BMPs' effectiveness). Work is needed to provide tools to help identify and select BMPs.

The Bear River Migratory Bird Refuge, Utah (the Refuge) serves as a critical resting and breeding area for several globally-significant populations of migratory birds. The Refuge covers 118.4 km^2 and is divided into 25 managed wetland units, each of which is separated by dikes and supplied with water through a series of canals controlled by gates [*Olson,* 2008]. This hydraulic infrastructure allows managers to manipulate water levels in each wetland unit with the main purpose to provide habitat for the wildlife. To date, Refuge managers are concerned about how they can secure and better allocate scarce water [*Endter-Wada et al.*, 2009] plus control invasive vegetation such as *Phragmites australis* (common reed) that reduces plant and animal biodiversity. Refuge managers currently control invasive *Phragmites* by applying herbicides followed by burning to remove *Phragmites.* Water allocation and management of invasive vegetation require time, staff and financial resources that in many cases are limited. Thus, managers need better tools to help them decide when and where to apply scarce management resources to most benefit their wetlands.

Research Contributions

This dissertation provides a set of management decision-support tools to improve water quality and wetland management. These tools are presented in three studies.

1. Simple Optimization Model to Reduce Phosphorus Loading in Water Bodies

The problem of excess of phosphorus load to a surface water reservoir is addressed by proposing:

- A simple linear optimization model that identifies the cost-minimizing mix of BMPs to implement within sub-watersheds to achieve required phosphorus load reduction targets for non-point phosphorus sources in a watershed.
- Use of the model at the Echo Reservoir Watershed suggests the most appropriate combination of BMPs within a sub-watershed and where to prioritize their implementation.

2. Nonlinear Optimization Model to Improve Diked Wetlands Management

Problems with water allocation and invasive vegetation in diked wetlands are addressed by developing a systems optimization model that integrates hydrological, ecological and management components. The main contributions include:

- Develop a novel approach to quantify wetland habitat performance and embed the habitat performance metric into a systems optimization model as an objective to be maximized.
- Develop a new systems optimization model to recommend water allocation and invasive vegetation control to improve wetland habitat of priority bird species. These recommendations are subject to constraints such as water availability,

spatial connectivity, hydraulic infrastructure capacities, vegetation responses, and available financial resources.

- Use of this model in the Bear River Migratory Bird Refuge shows opportunities to improve the wetland habitat of priority bird species.

3. Modeling Invasive *Phragmites* Spread in Wetlands

The second study was extended to investigate how invasive *Phragmites* spread in wetlands. The main contributions are:

- Develop an agent-based model to simulate invasive *Phragmites* spread as a function of water conditions and life stages of the plant. This model quantifies the spread of *Phragmites* spatially and temporally and provides a set of recommendations to decision makers to control invasive vegetation.
- Develop a novel method to embed results of the agent-based model into the system optimization model. The novelty of this method is to cross information between two different model approaches (agent-based and optimization each running at different spatial and temporal scales) with the purpose of representing the dynamic invasive vegetation response in a systems model and to recommend management strategies to improve wetland performance.
- Use of these tools at the Bear River Migratory Bird Refuge provides efficient ways to allocate water levels to minimize the invasive vegetation spread and improve wetland habitat performance simultaneously.

Dissertation Organization

The remainder of this dissertation is organized as follows: Chapter 2 presents a simple optimization model to help managers identify management strategies to reduce phosphorus levels in the Echo Reservoir watershed, Utah. Chapter 3 describes an approach to measure hydro-ecological performance in wetlands and embed it into an optimization model to improve wetland habitat for priority bird species. Chapter 4 develops an agent-based model approach to simulate invasive vegetation spread and extends the optimization model developed in Chapter 3 to include the dynamic invasive vegetation spread. Chapter 4 also describes the methodology to embed results and insights of an agent-based model into an optimization to recommend invasive vegetation control actions. Chapter 5 summarizes the three previous chapters, lists recommendations for managers, and suggests future work.

Chapters 2 to 4 are separate studies and include the problem identification, model development, and application to areas of study for the problems of water pollution and wetland management.

References

Cardwell, H., H. I. Jager, and M. J. Sale (1996), Designing instream flows to satisfy fish and human water needs, *J. Water Resour. Plann. Manage.*, *122*(5), 356-363.

Draper, A., M. Jenkins, K. Kirby, J. Lund, and R. Howitt (2003), Economic-engineering optimization for California water management, *J. Water Resour. Plann. Manage.*, *129*, 155.

Endter-Wada, J., T. Selfa, and L. W. Welsh (2009), Hydrologic interdependencies and human cooperation: The process of adapting to droughts, *Weather, Climate & Soc.*, *1*(1).

Harou, J., M. Pulido-Velazquez, D. E. Rosenberg, J. Medellín-Azuara, J. R. Lund, and R. E. Howitt (2009), Hydro-economic models: Concepts, design, applications, and future prospects, *J. Hydrol.*, *375*(3–4), 627-643.

Higgins, A. J., B. A. Bryan, I. C. Overton, K. Holland, R. E. Lester, D. King, M. Nolan, and J. D. Connor (2011), Integrated modelling of cost-effective siting and operation of flow-control infrastructure for river ecosystem conservation, *Water Resour. Res.*, *47*(5), W05519.

Olson, B. E. (2008), *Annual Habitat Management Plan*, US Department of the Interior, US Fish and Wildlife Service, Bear River Migratory Bird Refuge, Brigham City, Utah.

CHAPTER 2

SIMPLE OPTIMIZATION METHOD TO DETERMINE BEST MANAGEMENT PRACTICES TO REDUCE PHOSPHORUS LOADING IN ECHO RESERVOIR, UTAH[1]

Abstract

This study develops and applies a simple linear optimization program to identify cost effective Best Management Practices (BMPs) to reduce phosphorus loading to Echo Reservoir, Utah. The optimization program tests the feasibility of proposed Total Maximum Daily Load (TMDL) allocations based on potential BMP options and provides information regarding the spatial redistribution of loads among sub-watersheds. The current version of the TMDL for Echo reservoir allocates phosphorus loads to existing non-point phosphorus sources in different sub-watersheds to meet a specified total load. Optimization results show that it is feasible to implement BMPs for non-point sources in each sub-watershed to meet reduction targets at a cost of $1.0 million. However, relaxing these targets can achieve the overall target at lower cost. The optimization program and results provide a simple tool to test the feasibility of proposed TMDL allocations based on potential BMP options and can also recommend spatial redistributions of loads among sub-watersheds to lower costs.

[1] Reprinted from Water Resources Planning and Management Journal with permission from ASCE, Alminagorta, O., B. Tesfatsion, D. Rosenberg, and B. Neilson (2013), "Simple Optimization Method to Determine Best Management Practices to Reduce Phosphorus Loading in Echo Reservoir, Utah," Vol. 139(1), pages 122-125. "This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers."

2.1. Introduction

Many U.S. water bodies are impaired due to excessive nutrients. Excess nutrients such as phosphorus and nitrogen stimulate algae growth, reduce dissolved oxygen, and negatively impact aquatic habitat and water supplies for downstream urban and agricultural users. The Total Maximum Daily Load (TMDL) program provides a mechanism to improve the water quality of impaired water bodies and meet the associated in-stream water quality standards and designated uses. Typically TMDLs provide information regarding the current pollutant loads to an impaired water body and then present a plan to reduce and reallocate loads among pollutant sources to meet the in-stream water quality standard. TMDLs often require the use of best management practices (BMPs) to reduce contaminant loads from non-point sources such as farms, range land, and animal feeding operations. In these instances, identifying, selecting, and locating BMPs is a concern (Maringanti et al. 2009).

To address this issue, researchers have applied optimization techniques to select BMPs and determine load allocation strategies at the farm and field scale. These techniques include a multiobjective genetic algorithm (GA) and a watershed simulation model to select and place BMPs (Maringanti et al. 2009), a GA to search the combination of BMPs that minimized cost to meet pollution reduction requirements (Veith et al. 2004), and an optimization model based on discrete differential dynamic programming to locate BMPs in a watershed considering economic analysis (Hsieh and Yang, 2007). While useful, the approaches require complex solution techniques, long computation times, and have seen limited use by decision makers and regulators. Here, we present a simple linear optimization tool to identify cost-effective BMPs to implement at the sub-

watershed scale that meet the allocation required by a TMDL. We also test allocation feasibility and show how to spatially reallocate loads among sub-watersheds to improve feasibility and lower costs. The utility of this tool is presented in the context of a pending TMDL for phosphorus at Echo Reservoir in Utah, U.S. Here, we consider the non-point sources and load-reduction strategies identified by the pending TMDL for Echo Reservoir; however our tool is general and can accommodate other point and non-point sources and remediation strategies.

2.2. Study Area and Pending TMDL

Echo Reservoir is located on the Weber River in northeastern Utah (Figure 2.1). There are two upstream reservoirs, Wanship and Smith & Morehouse, and three main sub-watersheds that drain to Echo: Weber River above Wanship, Weber River below Wanship, and Chalk Creek.

In response to sustained dissolved oxygen concentrations below 4 mg/L and phosphorus concentrations above the state standard of 0.025 mg/L in Echo Reservoir, the Utah Department of Environmental Quality (UDEQ), Division of Water Quality has submitted a TMDL for Echo Reservoir (Adams and Whitehead, 2006; hereafter, the "pending TMDL"). The pending TMDL identifies several major non-point sources of phosphorus (Table 2.1). Additional phosphorus sources to the reservoir were identified as internal reservoir loading and several point sources.

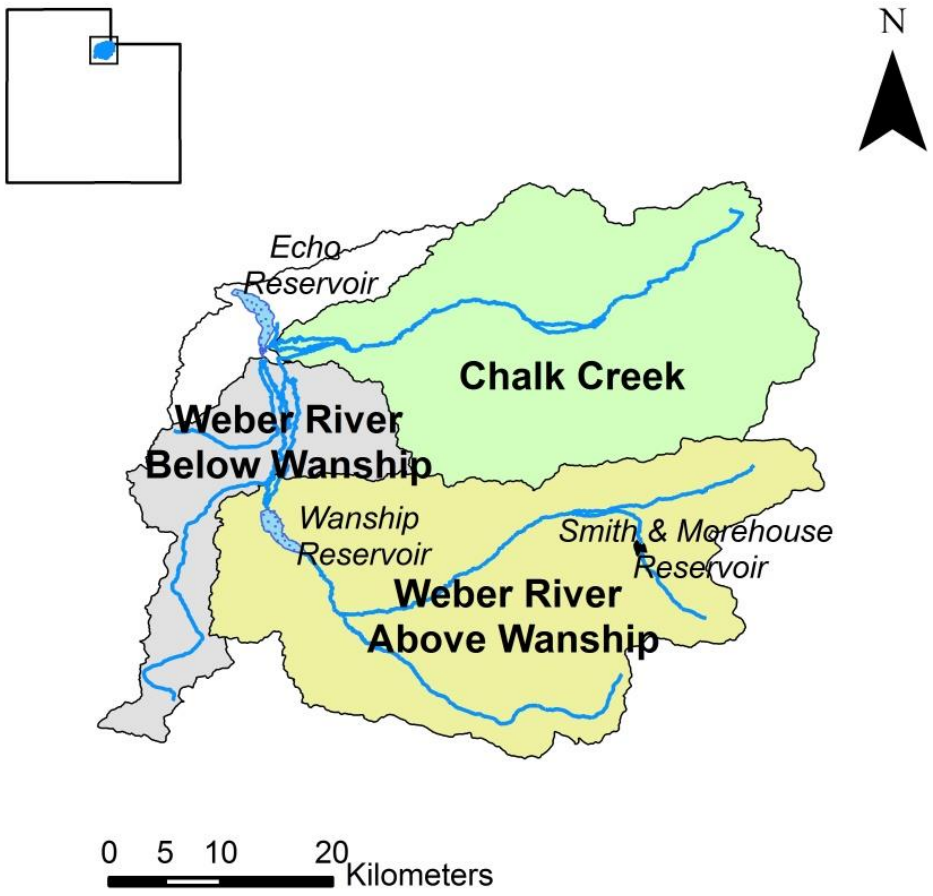

Figure 2.1. Location of Echo Reservoir

According to the pending TMDL, the target load reduction for the three primary non-point sources (land applied manure, private land grazing and diffuse runoff) is 8,067 kg per year. Here, loads refer to total sub-watershed loads delivered to the sub-watershed outlet rather than loads delivered to the receiving water body of concern (i.e., Echo Reservoir). The load reduction is calculated based on a permissible load of 19,800 kg phosphorus per year at the inlet to the Echo Reservoir to maintain its beneficial use. This permissible load was identified through a modeling effort (hereafter referred to as the instream water quality model) that simulates the major physical, chemical, and biological processes affecting total phosphorus and dissolved oxygen concentrations within the

stream and reservoir (Adams and Whitehead, 2006). After determining the permissible load, UDEQ sought public involvement and investigated existing plans in the study area to implement Best Available Technologies (BATs) and BMPs (for point and non-point sources, respectively).

Table 2.1. Assignment of Applicable BMPs to Non-Point Sources

Source	Description	Applicable BMPs
Direct run off from AFOs	Animal wastes containing phosphorus from watershed animal feeding operations (AFOs) directly runoff into nearby water bodies.	None
Land applied manure	Animal waste applied on agricultural land as a fertilizer is incorporated into the soil and subsequently washed into a nearby water body.	Grass filter strips, Conservation tillage, Manage agricultural nutrients.
Public land grazing	Animals grazed on public lands leave waste containing phosphorus that is subsequently washed into a nearby water body.	Protect grazing land, Fence streams, Grass filter strips.
Private land grazing	Animals grazed on private lands leave waste containing phosphorus that is subsequently washed into a nearby water body.	Protect grazing land, Fence streams, Grass filter strips.
Septic Systems	Domestic leak wastewater into nearby waterways when septic tanks are installed incorrectly or are too close to a waterway.	None
Diffuse Runoff	Phosphorus loading that arises from fertilizers, pesticides, trails, roads, dispersed camping sites and erosion from up slopes areas.	Retire land, Stabilize stream banks, Cover crops, Grass filter strips, Conservation tillage, Manage agricultural nutrients, Sprinkler irrigation.

Using available BATs and BMPs, they allocated phosphorus loads among sources and between the three sub-watersheds. Interestingly, the pending TMDL allows point sources to maintain their current discharges (many have already implemented BATs) and focuses phosphorus reduction efforts only on non-point sources. While the pending TMDL prescribes the total load allocations for non-point sources at the sub-watershed

level, it does not present a specific plan to achieve these load reductions nor does it consider the feasibility to meet required reductions.

2.3. Simple Optimization Tool

We developed a simple optimization tool that identifies the cost minimizing mix of BMPs to implement within sub-watersheds to achieve required phosphorus load reduction targets for non-point phosphorus sources in a watershed. Two scenarios were analyzed: first, include reduction targets for each non-point source in each sub-watershed as specified in the TMDL. Second, we relax and combine the sub-watershed reduction targets to generate global, watershed-wide reduction targets for sources across all sub-watersheds. Both scenarios can be formulated as a linear program as follows:

2.3.1. Identify phosphorus sources and reduction targets by sub-watershed;

2.3.2. Identify potential BMPs for each source, characterize BMP unit cost and reduction efficiency, and determine the available land area or reach length to implement BMPs in each sub-watershed; and

2.3.3. Formulate and implement the linear optimization program.

Step 1 was prescribed in the pending TMDL and our analysis considers reduction targets (p; kg P/year) for three non-point phosphorus source types s in three sub-watersheds w, as mentioned previously.

Potential BMPs to reduce phosphorus from non-point sources in the Echo watershed include actions such as retiring land, protecting grazing land, cover cropping, grass filter strips, conservation tillage, managing agricultural nutrients, and switching to sprinkler irrigation. All of these BMPs can be implemented on available land (Table 2.1). Additionally considered are fencing and bank stabilization that can be implemented along

river and stream reaches (Table 2.1). Horsburgh et al. (2009) present estimates for unit phosphorus removal costs of each BMP *i* (u_i; $/kg P) and efficiencies (e_i ; kg P/km^2 or kg P/km) applied in the nearby Bear River basin. These estimates are used in this study to demonstrate the simple optimization analysis.

BMP effectiveness to reduce phosphorus also depends on the resources available to implement BMPs in a particular sub-watershed *w* (b_{gw}; km^2 or km). Here, *g* indicates available land area or stream bank length. For example, to reduce phosphorus loading from private land grazing in the Chalk Creek sub-watershed, we need to identify the area of this specific land use available within the sub-watershed. Similarly, to reduce phosphorus loading from these same land uses by fencing streams, the length of stream that can be fenced must be identified. For this case study, land use areas were taken from the pending TMDL and stream lengths were estimated from widely available stream reach coverage.

With known phosphorus load reduction targets, BMP costs, effectiveness, and available land area or stream length for implementation, we can formulate and implement the linear optimization program. The program determines phosphorus mass removed (P_{iws}; kg P/year) and implementation levels (B_{iws}; km^2 or km) for each BMP in each sub-watershed for each source to minimize costs and achieve the phosphorus load reduction target. Mathematically, the objective function minimizes the sums of removal costs for all BMPs *i* in all sub-watersheds *w* and for all sources *s*:

$$min \sum_{iws} \left(u_i \times P_{iws} \right) \tag{2.1}$$

and is subject to:

- The definition of phosphorus mass removed by each BMP *i* in each sub-watershed *w* and at each phosphorus source *s:*

$$P_{iws} = e_i \times B_{iws}; \forall\, i,s,w \tag{2.2}$$

- The phosphorus removal, which must meet or exceed load reduction targets for each source *s* in each sub-watershed *w*:

$$\sum_i \left(c_{is} \times P_{iws}\right) \geq p_{ws}; \forall w, s \tag{2.3}$$

- The BMP implementation limited by available land area or stream length *g* in each sub-watershed *w,* as well as other BMPs already implemented:

$$\sum_s \sum_i \left(c_{is}\ x_{gi}\ B_{iws}\right) \leq b_{gw}; \forall g,w \tag{2.4}$$

- The phosphorus removal, which must not exceed the existing load (l_{ws}; kg) in each sub-watershed *w* and for each source *s*:

$$\sum_i \left(c_{is} \times P_{iws}\right) \leq l_{ws}; \forall w, s \tag{2.5}$$

- Non-negative decision variables:

$$P_{iws} \geq 0; \forall\, i,w,s\ \ ; B_{iws} \geq 0; \forall\, i,w,s \tag{2.6}$$

In Equations (2.3-2.5), c_{is} is a matrix whose elements take the binary value 1 if BMP *i* can be applied to source *s,* and 0 otherwise. Each column of *c* has at least one non-zero element because at least one BMP can be implemented for each source. x_{gi} is also a matrix whose elements take the binary value 1 if implementing BMP *i* precludes

implementing another BMP on the same land parcel or stream reach segment *g*, and 0 otherwise. Each row *g* also has at least one non-zero element, corresponding to one or more BMPs. Note, BMPs are applied on either an area or stream length basis. Corresponding implementation levels and removal units must be used in Equations (2.2) and (2.4).

As presented in the pending TMDL, phosphorus reduction targets in Equation (2.3) are source and sub-watershed specific. However, these sub-watershed specific reduction targets can be relaxed and combined to give global reduction targets across the entire watershed for each source (Equation 2.7).

$$\sum_{i}\sum_{w}\left(c_{is}\times P_{iws}\right)\geq\sum_{w}p_{ws};\forall s \tag{2.7}$$

These global targets allow reductions and re-allocations among sub-watersheds and assume phosphorus loadings from each sub-watershed strictly and linearly add to produce the total load to the receiving body, Echo Reservoir. This assumption is appropriate since the TMDL sub-watershed targets were determined by linearly decomposing the target load for the reservoir (Adams, personal communication, Nov. 03, 2010).

Equations (2.1) through (2.6) represent the sub-watershed specific load reduction scenario 1, dictated by the pending TMDL whereas Equations (2.1), (2.2), and (2.4 – 2.7) represent scenario 2, a more relaxed scenario, where reductions can be shifted across sub-watersheds. Equations for both scenarios can be solved using either the Excel add-in Solver or other linear program software packages.

2.4. Results and Discussion

The optimization program results for the first scenario suggest that BMPs for private land grazing, diffuse runoff, and land applied manure phosphorus sources can feasibly reduce phosphorus loads in Chalk Creek, Weber River below, and Weber River above Wanship sub-watersheds to targets prescribed by the pending TMDL (Table 2.2, Scenario 1).

Table 2.2. Summary of Required Phosphorus Load Reductions, Model-Recommended BMPs, Load Reductions Achieved, and Costs.

Scen.	Sub-watershed[a]	Required reduction (kg/yr)	Protect grazing land[b] (kg/yr)	Stabilize stream banks[c] (kg/yr)	Conser-vation tillage[d] (kg/yr)	Manage agricultural nutrients[d] (kg/yr)	Total reduction (kg/yr)	Total cost ($1000)
1	Chalk creek	2,038	354	915	87	682	2,038	242
	WBW	1,458	155	549		754	1,458	172
	WAW	4,572	372	1,352		2,848	4,572	587
	Total	8,067	880	2,816	87	4,283	8,067	1,000
2	Chalk creek		880	2,816		682	4,379	367
	WBW					942	942	158
	WAW					2,747	2,747	460
	Total	8,067	880	2,816		4,370	8,067	985

[a]WBW = Weber below Wanship, WAW= Weber above Wanship.
[b] BMP to reduce phosphorus loading from private land grazing source.
[c] BMP to reduce phosphorus loading from diffuse runoff source.
[d] BMP to reduce phosphorus loading from land applied manure source.

These reductions are achieved by implementing protecting grazing land, stabilizing stream banks, and managing agricultural nutrients BMPs in all sub-watersheds and conservation tillage in Chalk Creek. When considering reduction targets specific for each sub-watershed, the available BMPs can achieve the overall reduction target at a cost

of $1.0 million. Sensitivity range-of-basis results indicate all BMP cost and removal efficiency parameters (except conservation tillage in Chalk Creek) can increase by factors of 1.7 and more before changing the optimal mix of BMPs (results not shown, for brevity).

There may be cases where there is insufficient land area or stream length to implement BMPs in a specific sub-watershed. Or, it may be more cost effective to implement BMPs in other locations. When considering these instances, we can relax sub-watershed specific reduction targets, and instead specify an overall reduction target for the entire watershed. For the Echo Reservoir watershed, we can feasibly achieve the watershed-wide reduction target at a lower cost (Table 2.2, Scenario 2) by curtailing more expensive conservation tillage and increasing the less expensive BMP to manage agricultural nutrients in the Weber Basin below Wanship. Additionally, the program shifts protecting grazing land, stream bank stabilization, and some managing agricultural nutrients to the Chalk Creek and Weber below Wanship sub-watersheds. However, these later shifts do not affect the overall implementation costs since the model assumes BMP costs are the same across sub-watersheds. These changes are all possible because there is additional land area and stream length available to implement BMPs in the Chalk Creek and Weber Basin below Wanship sub-watersheds beyond those needed to meet sub-watershed reduction targets prescribed by the pending TMDL. Since this reallocation of loads only provides information regarding the total watershed loads to Echo Reservoir rather than delivered loads, the second scenario requires further use of the instream water quality model to verify that the reservoir standard is still met. In the case of Echo Reservoir, specifying overall source reduction targets for the entire watershed may allow

managers to shift BMP implementation among sub-watersheds to meet the overall reduction target for Echo Reservoir at a lower cost.

Beyond verifying that shifting loads across sub-watersheds still meets the reservoir standard, we note that these results rely on available linear estimates of BMP unit costs and effectiveness. These linear estimates mean that the model assumes the load at a sub-watershed outlet scales linearly irrespective of where the BMP will be located in the sub-watershed. While this assumption is likely appropriate when a BMP is implemented over all the available land or stream bank resource in a sub-watershed, there are cases where locating a BMP near a stream and/or the sub-watershed outlet can significantly affect load reductions. In this case, we assume that each site contributes a variable load reduction that, on average, reflects the modeled unit effectiveness value. However, when model results suggest available land or stream-bank resources go unused, managers and regulators must apply their local expert knowledge to select farm, field, or stream bank sites where BMP implementation will most effectively reduce the load at the sub-watershed outlet.

We further note that implementing a watershed BMP program may allow for some economies of scales. These economies are readily included in the optimization tool with integer decisions and filling constraints. However, economies-of-scale data are not currently available and sensitivity analyses on the cost and efficiency parameters suggest this level of detail may not be needed. Obviously, the model outputs and results are as good as the input data describing BMP costs, efficiencies, existing loads, reduction targets, and available land and stream bank lengths to implement BMPs; gathering

additional information within the Echo Reservoir watershed can increase accuracy and confidence in the optimization results.

2.5. Conclusion

We developed a simple linear optimization tool that identifies cost-effective strategies to reduce phosphorus loads from sources to prescribed targets. We applied this tool to Echo Reservoir on Weber River, Utah and showed that BMPs for non-point private land grazing, diffuse runoff, and land applied manure sources can feasibly reduce phosphorus loads to sub-watershed target levels identified within the pending TMDL. Relaxing the sub-watershed reduction targets suggests a global reduction target for the reservoir, which can be reached at lower cost. This global strategy still requires further verification using more detailed instream water quality modeling. This optimization tool offers a simple way to test the implementation feasibility of a proposed TMDL allocation, and suggest how loads can be spatially redistributed among sub-watersheds to lower phosphorus loads and reduce costs.

Notation

The following symbols are used in this study:

B_{iws} = implementation levels for each BMP *i*, sub-watershed *w*, and source *s*.

b_{gw} = resources available to implement BMPs in a particular sub-watershed *w*.

c_{is} = a binary parameter that takes the value 1 if BMP *i* can be applied to source *s* and 0 otherwise.

e_i = estimated unit phosphorus removal efficiencies for each BMP, *i*

g = row on the model to select available resource (parcel area or reach length).

i = best management practice.

l_{ws} = existing phosphorus load in sub-watershed w from source, s.

P_{iws} = phosphorus mass removed by each BMP i in each sub-watershed w targeted at each phosphorus source s.

p_{ws} = phosphorus reduction targets for sub-watershed w and non-point source, s.

s = non-point source of phosphorus.

u_i = estimate for unit phosphorus removal costs for each BMP, i .

w = sub-watershed.

x_{gi} = a binary parameter that takes the value 1 if implementing BMP i precludes implementing another BMP on the same land parcel or stream reach segment g, and 0 otherwise.

References

Adams, C., and Whitehead, J. (2006). "Echo reservoir TMDL water quality study." Utah Dept. of Environmental Quality — Division of Water Quality, Salt Lake City, Utah. ⟨http://www.waterquality.utah.gov/TMDL/Echo_Reservoir_TMDL.pdf⟩ (Apr. 7, 2010).

Horsburgh, J. S., Mesner, N. O., Stevens, D. K., Caplan, A., Glover, T., and Neilson, B. T. (2009). "USEPA targeted watersheds grant Bear River Basin." *Final Project Rep., Project # WS-97807301*, Utah State Univ., Logan, UT.

Hsieh, C., and Yang, W. (2007). "Optimal nonpoint source pollution control strategies for a reservoir watershed in Taiwan." *J. Environ. Manage.*, 85(4): 908 – 917.

Maringanti, C., Chaubey, I., and Popp, J. (2009). "Development of a multiobjective optimization tool for the selection and placement of best management practices for nonpoint source pollution control." *Water Resour. Res.*, 45, 1 – 15.

Veith, T., Wolfe, M., and Heatwole, C. (2004). "Cost-effective BMP placement: Optimization versus targeting." *Trans. ASAE*, 47(5), 1585 – 1594.

CHAPTER 3

SYSTEMS MODELING TO IMPROVE THE HYDRO-ECOLOGICAL PERFORMANCE OF DIKED WETLANDS[2]

Abstract

Habitat loss, invasive vegetation, and water shortages have degraded wetland ecosystems and create the need to efficiently allocate scarce resources to manage wetlands. Management requires performance metrics that quantify habitat degradation and measure the progress towards achieving specific goal(s). Here, we developed an approach to quantify the hydro-ecological performance of diked wetlands and embed this performance into a systems optimization model to recommend water allocation and invasive vegetation control and improve habitat for wetland birds. First, we measure the hydro-ecological performance for wetlands using the weighted usable area that represents the available wetland surface area that provides suitable hydrological and ecological conditions for priority bird species. Second, we subject model recommendations for water allocations and invasive plant management in wetlands to constraints like water availability, spatial connectivity of wetland units, hydraulic infrastructure capacities, plus financial and time resources available to manage invasive vegetation and water. Third, we applied the model at the Bear River Migratory Bird Refuge, which is the largest wetland complex on the Great Salt Lake, Utah. Comparing model-recommended management actions to past Refuge water and vegetation control activities found that increasing and more dynamically managing water levels can triple wetland performance. Additional modelling scenarios show that wetland performance is more sensitive to gate

[2] Coauthored by David E. Rosenberg and Karin M. Kettenring.

operation, water availability, and changes in vegetation response than changes in the financial budget. The approach demonstrates a framework to develop and apply hydro-ecological performance metrics for wetlands, embed those metrics into an optimization model, and recommend management strategies to improve wetland performance.

3.1. Introduction

Water shortages, wetland drainage, invasive vegetation, agricultural and sub/urban land use have degraded wetland ecosystems and caused flood damage, soil erosion, sedimentation, pollution and loss of biodiversity. These changes have also impacted wetland ecosystem functions and services [*Kusler, 2003*] and spurred needs to quantify habitat degradation, understand the main factors affecting wetland habitat, and assess management options to improve wetland habitat.

To improve wetland habitat, managers can manipulate hydrologic parameters such as the magnitude and frequency. Managers can also alter the timing of flooding to affect species biology including reproduction, growth, and survival and varied wetland plant distributions [*Batzer and Sharitz,* 2006]. Water-level changes are a primary factor that help maintain wetland diversity [*Johnson et al.*, 1997; *Smith et al.*, 2008] and lead some researchers to suggest manipulating water levels and timing of flows to improve habitat for water birds [*Taft et al.*, 2002; *Bolduc and Afton*, 2008]. Several projects have managed water in wetlands to provide habitat to waterbird communities with notable examples in Florida (Everglades), Australia (Lower Gwydir) and Utah (Jordan River floodplain) [*Walters et al.*, 1992; *Davis et al.*, 2001; *McCulley*, 2009].

Wetland managers can also control invasive vegetation such as *Phragmites australis* (common reed, hereafter *Phragmites*). *Phragmites* distribution and abundance

has increased dramatically in North America over the past 150 years [*Saltonstall*, 2002]. *Phragmites* 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 [*Chambers et al.*, 1999; *Ailstock et al.*, 2001; *Smith et al.*, 2008], excessive spread of *Phragmites* can 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 [*Ailstock et al.*, 2001] – plays an important role in managing wetland habitat [*Herrick and Wolf*, 2005]. At the same time, control activities require time, staff, and financial resources that in many cases are limited. Therefore, managers often want to know when and where to apply scarce management resources to most benefit their wetlands.

Systems optimization models can connect these physical, hydrological, management, and other system components and help managers identify efficient ways to allocate scarce water, financial, and other resources to achieve a stated management goals [*Hof and Bevers*, 2002]. Typically, systems models quantify non-ecological objectives such as water volume, supply reliability [*Loucks et al.*, 2005], cost [*Harou et al.*, 2009], economic net benefits [*Fisher et al.*, 2005; *Harou et al.*, 2009], social equity [*Mirchi et al.*, 2010], or proximity to a target. When considered, environmental and ecological aspects typically are included as static constraints such as that water allocations must obey a minimum in-stream flow value that guarantee fish survival [*Vogel et al.*, 2007]. A small but growing literature is moving beyond constraint methods to include one or multiple environmental and ecological objectives in a systems model. For example, *Cardwell et al.* [1996] developed a multi-objective optimization model to select the

magnitude and frequency of stream flows that maximize species population under water availability constraints. *Stralberg et al.* [2009] developed a mixed integer model to recommend water depth and salinity management strategies to maximize avian abundance under wetland area availability constraints in San Francisco Bay. *Higgins et al.* [2011] developed a non-linear integer programming model to recommend investments in operation and flow control structures to minimize changes of the natural flow regime in the Murray River-Australia. Important work remains to define and quantify hydro-ecological performance metrics for wetlands and embed the metrics as objective functions in optimization models that can recommend management actions to improve wetland ecological services.

In this chapter, first, we define a hydro-ecological performance metric to quantify wetland habitat. We measure performance using an intermediate and overall performance metric. The intermediate metric is the habitat suitability index (H) that represents the capacity of a given habitat to support selected indicator species. We combine these indices with the wetland flood area and species weights to create an overall metric defined as the weighted usable area for wetlands (WU). The WU represents the surface area available in the wetland that provides suitable hydrological and ecological conditions for selected indicator species. Second, we embed the hydro-ecological performance metric as an objective function in a systems optimization model that recommends water allocations among diked wetland units and vegetation management actions to improve the wetland ecosystem performance. Water allocation and vegetation management decisions to improve the WU are subject to different constraints such as availability of water, spatial connectivity of supply canals, hydraulic infrastructure, and

budget limitations. We apply the model at the Bear River Migratory Bird Refuge, Utah (hereafter, the Refuge), which is a large wetland complex located on the northeast shore of the Great Salt Lake, Utah. The Refuge serves as a critical resting and breeding area for several globally-significant populations of migratory birds. Refuge managers have a pressing need to better allocate scarce water and control invasive vegetation to promote diverse habitat types and support a variety of bird species [*Olson*, 2008].

3.2. Systems Model

Systems optimization models provide a general framework to connect and study interactions among interdependent system components. Managed wetlands are complex ecosystems that involve interactions among hydrological (e.g., water availability), ecological (e.g., species requirements), engineering (e.g., water distribution infrastructure), management (e.g., invasive vegetation control), and economic (e.g., recreation) components. To deal with this complexity, we present a general approach to develop a systems model to improve the ecological performance in a study system such as wetlands. The approach includes six phases:

Phase 1. Identify the management goal(s).

Phase 2. Identify performance metrics. Here, quantify and describe how to measure progress towards achieving the goal(s) identified in phase one.

Phase 3. Identify decision variables. Identify what actions managers can take to improve performance and achieve their goals.

Phase 4. Mathematically relate the decision variables and performance metrics.

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

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

The identification of components in each phase depends on the study system, main management goals, such as improving bird habitat or recreation services, and the characteristics of the ecosystem to improve. For example, in natural wetlands, water management can-not be a decision variable because it is not possible to manipulate water level. These components are applied in managed wetlands (hereafter, diked wetlands). Diked wetlands provide the water control facilities to manipulate the frequency, duration and depth of water to meet management goals. Also, diked wetlands are more susceptible to invasion by non-native vegetation because of the higher level of disturbance (e.g., dike construction, burning). Hence, water allocation and management of suitable vegetation are key components in diked wetlands to reach specific management goals such as provide suitable habitat to waterfowl.

Here, we focus on diked wetlands at the Bear River Migratory Bird Refuge (Utah), which are characterized to have the hydraulic infrastructure (e.g., canal, gates) to manage wetlands as well as the need to control invasive vegetation (Figure 3.1). The overall goal - identified through participatory meetings with stakeholders - is to support the diversity of wetland bird species and plant communities to mimic a well-functioning wetland ecosystem with multiple birding, hunting, and other ecosystem services.

Managers of diked wetlands can reach these goals by controlling: (i) water depths in wetland units and (ii) invasive vegetation cover using herbicides and burning. Water management decisions are influenced by water availability, network conveyance, canal

capacities, evaporation rates, and gate operation, while the effectiveness of invasive vegetation control is influenced by natural growth of invasive vegetation, prior vegetation cover, and the available financial budget to reduce invasive vegetation.

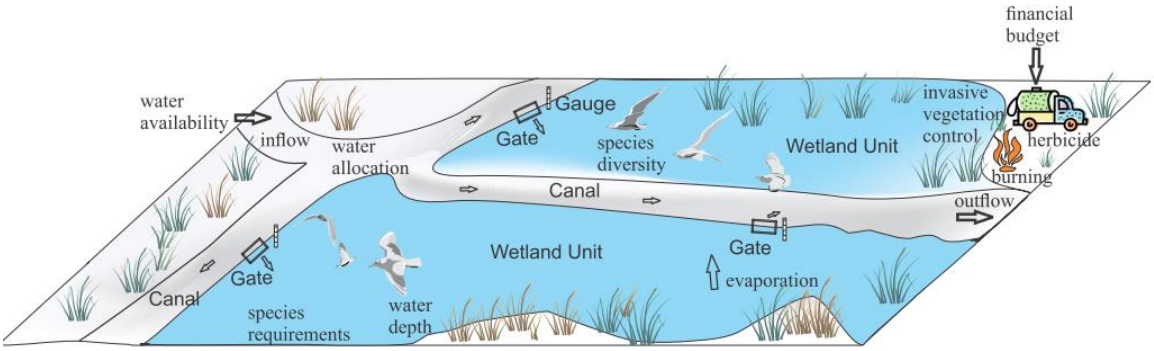

Figure 3.1. Major components of the systems model for diked wetlands at the Refuge.

Below, we describe the methodology used to formulate a systems model to achieve the wetland management goals subject to the available decision variables and constraints.

3.2.1. Wetland Management Purposes

We formulated the systems model assuming that the main management purpose is to maximize the wildlife habitat to promote diverse habitat types, support a variety of bird species, and mimic a well-functioning wetland. We synonymously call this objective maximizing wetland habitat performance.

3.2.2 Performance Metrics

We quantify wetland habitat performance using intermediate and overall performance metrics. The intermediate metric is the habitat suitability index [*H* (unitless)] that represents the capacity of a given habitat attribute (such as water depth or

vegetation cover) to support selected bird species. Suitability ranges from 0 (poor) to 1 (excellent) habitat quality. Habitat suitability has been used for two decades to define the quality of the habitat for different wildlife species (e.g. fish, alligators, birds, algae) [*Tarboton et al.*, 2004]. In the present study, the habitat suitability index is an adaptation of the methodology implemented by the U.S. Fish and Wildlife Service to evaluate the environmental impact of development projects [*Downey*, 2004].

Habitat suitability indices are combined with weight by species, and the wetted surface area to create the overall performance metric defined as the weighted usable area for wetlands [*WU*, measured in square meters (m^2)]. The *WU* represents the available surface area that provides suitable hydrological and ecological conditions for priority bird species. This method adapts to the weighted usable area method which is one of the most widely used approaches for evaluating in-stream flow needs [*Cardwell et al.*, 1996; *Payne*, 2003; *Hardy*, 2005]. Next, we introduce the decision variables, then later in section 3.2.4, we mathematically relate these decision variables to the intermediate habitat suitability index to develop the hydro-ecological performance metric and objective function for the wetland study system.

3.2.3. Decision Variables

Wetland managers make hydrological and vegetation management decisions. In the model, hydrological decisions include: the flow rate [$Q_{t,i,j}$ (ha-m/month)] during time t (month) conveyed from node i (a location index) to another node j (an alias of the index i). Additional hydrological decisions are the water depth [$WD_{t,w}$ (m)], storage [$S_{t,w}$ (ha-m)], and flood area [$A_{t,w}$ (m^2)] at time t at the subset of nodes w that are wetland units ($w \in i$; storage is constrained to be zero at the remaining nodes that are simple junctions).

The observed water depth-storage-area relationships for wetland units allow us to mathematically relate the different hydrological variables and we use the lower-case notation wd_w and a_w [$WD_{t,w} = wd_w(S_{t,w})$; $A_{t,w} = a_w(S_{t,w})$] to refer to these relationships.

The second type of decision variable represents invasive vegetation cover [$IV_{t,w}$ (quantified by a percentage as the affected area within a wetland unit w in time t divided by the total area of the wetland unit)] and vegetation removal [$RV_{t,w}$ (quantified by a percentage as the removed invasive vegetation area within a wetland unit divided by the total area of the wetland unit)]. The invasive vegetation cover variables track the ecological states of wetland units. The complement of the invasive vegetation cover (100 - IV), corresponds to other classes of wetland land use such as native vegetation, open water, uplands.

3.2.4. Relationships between Decision Variables and Performance Metrics

The relationship between decision variables (water depth, invasive vegetation cover) and wetland performance is made in two stages. First, we relate independent decision variables with the intermediate performance metric (habitat suitability index) through habitat suitability curves (Figure 3.2). These curves allow us to identify how changes in decision variables (e.g., invasive vegetation coverage) can affect the quality of habitat of specific species, which is further described below. The second stage combines habitat suitability index with weight by species, and the wetted surface area to relate with the main performance metric defined as weighted usable area for wetlands. Therefore, changes in water levels and invasive vegetation cover can be represented in habitat suitability curves and the weighted usable area for wetlands. Habitat suitability curves are based on literature review, historical data, controlled experiments, and expert opinion

[*Hardy*, 2005]. We use habitat suitability curves because it allows us to: (i) measure how habitat of bird species is affected by the relevant decision variables (e.g., water levels and invasive vegetation coverage), and (ii) tractably incorporate the relationship in a non-linear systems optimization model. Figure 3.2 shows the relationship between invasive vegetation (*Phragmites*) coverage at the Refuge and habitat suitability for a priority bird species (Black necked stilt - *Himantopus mexicanus*). Habitat suitability ranges from 0 (poor) to 1 (excellent) habitat quality. When *Phragmites* stand comprises more than 10% of the total area of a wetland unit, habitat becomes undesirable for priority bird species because *Phragmites* spreads rapidly and displaces aquatic vegetation with higher wildlife values (i.e., habitat suitability index values approach to 0) [*Olson*, 2007].

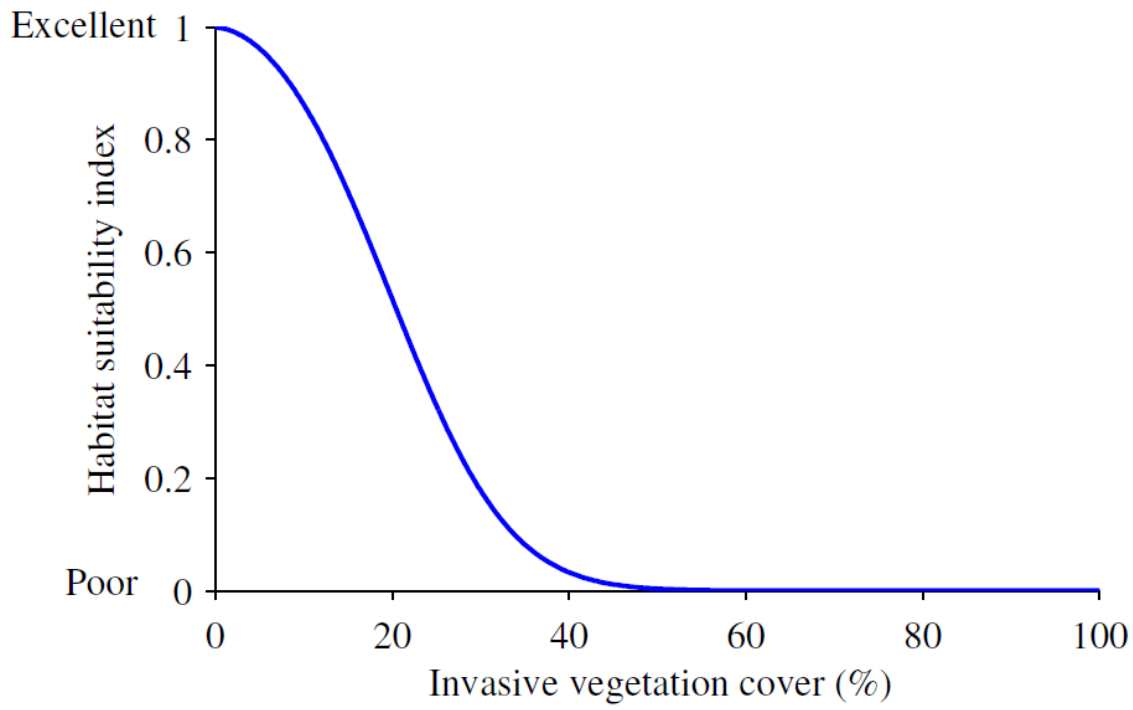

Figure 3.2. Example habitat suitability index based on invasive vegetation cover (*Phragmites)*.

Mathematically, habitat suitability associated with the invasive vegetation cover attribute [$HV_{t,w,s}$ (unitless)] is a function (fv_s) of the invasive vegetation cover (IV, defined previously) at each time t, wetland unit w, and for each priority species s (Eq. 3.1).

$$HV_{t,w,s} = fv_s\left(IV_{t,w}\right), \quad \forall t,w,s \tag{3.1}$$

where fv_s is a continuous and smooth non-linear function to avoid numerical difficulties in the model solution [*McCarl et al.*, 2008].

Similarly, the habitat suitability associated with the water depth attribute [$HW_{t,w,s}$ (unitless)] is a function (fw_s) of water depth ($WD_{t,w}$) which is itself a function of storage ($S_{t,w}$) for each time t, wetland unit w, and species s (Eq. 3.2).

$$HW_{t,w,s} = fw_s\left[wd_{t,w}\left(S_{t,w}\right)\right], \quad \forall t,w,s \tag{3.2}$$

Here again, fw_s is a smooth, continuous, non-linear function and $wd_{t,w}$ and $S_{t,w}$ are as defined previously.

The objective function (Eq. 3.3) maximizes the sum of the weighted usable area for wetlands (WU) across time and wetland locations and allows us to quantify wetland performance in units of area (m^2). In the objective function, WU is the product of two expressions: the first expression, shown in square brackets, combines species-specific habitat suitability indices for water depth (HW) and invasive vegetation cover (HV) habitat attributes; we combine individual habitat suitability components multiplicative to represent how wetland habitat performance is affected by independent habitat components simultaneously. For example, to provide habitat to bird species in wetlands, both habitat conditions (suitable water depth and suitable vegetation cover) need to

happen together. It will not be possible to provide habitat condition to bird species even when there are favorable vegetation cover conditions in wetlands (e.g., invasive vegetation cover less than 10% of the wetland unit), if still there are unfavorable hydrologic conditions (e.g., dry wetland unit). Also, we use the weighting parameter, $sw_{t,s}$ (unitless) to prioritize among species *s*, in a particular time *t*. The weighting parameter allows us to consider the varying and possibly conflicting habitat needs of different species. We call the first expression in square brackets a composite habitat suitability, $HC_{t,w}$ (unitless), and it identifies the level of habitat suitability (ranging between 0 and 1) that considers water depth, vegetation cover requirements, and species prioritization factors. The second expression, $a_{t,w}$ ($S_{t,w}$) is the flooded area that scales the composite habitat suitability into measureable units of surface area. Together, the objective function maximizes the surface area available with suitable condition for priority species.

$$MaximizeWU = \sum_{t,w}\left[\left(\frac{\sum_{s} sw_{t,s}\cdot HW_{t,w,s}\cdot HV_{t,w,s}}{\sum_{s} sw_{t,s}}\right)\cdot a_{t,w}\left(S_{t,w}\right)\right] \tag{3.3}$$

3.2.5. Constraints

The model has hydrological, ecological, and management constraints (Eqs 3.4-3.10). The main hydrological constraints require water mass balance at each time *t* and node *i* (Eq. 3.4) and place minimum and maximum limits on channel conveyance and storage in wetland units (Eqs. 3.5-3.6).

$$in_{t,i} + \sum_{j} lq_{j,i}\cdot Q_{t,j,i} - \sum_{j} Q_{t,i,j} - le_t \cdot a_{t,i}\left(S_{t,i}\right) = S_{t,i} - S_{t-1,i} \quad , \quad \forall t,i \tag{3.4}$$

$$qm_{ij} \le Q_{t,i,j} \le qx_{ij} \quad , \quad \forall t, i, j \tag{3.5}$$

$$sm_i \le S_{t,i} \le sx_i \quad , \quad \forall t, i \tag{3.6}$$

In these equations $in_{t,i}$ (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; sm_i and sx_i (each ha-m) are, respectively, the minimum and maximum water storage capacity at node i; and Q, a, and S are as defined previously. Note, storage at time zero ($S_{t=0}$) equals the initial storage at node i. Also, setting sm and sx to zero defines a simple hydraulic junction with no storage; in this case only the first three terms of mass balance constraint (3.4) are active. Again, w refers to the subset of nodes representing wetland units that allow storage ($sx > 0$) and where ecological performance is measured.

Ecological constraints account for changes in invasive vegetation cover in wetland units through time (Eq. 3.7).

$$IV_{t,w} = IV_{t-1,w} - RV_{t,w} + vr_{t,w} \quad , \quad \forall t, w \tag{3.7}$$

where $IV_{t,w}$ and $RV_{t,w}$ are the invasive vegetation cover and removal vegetation respectively (expressed as percentages of the wetland unit area) as defined previously, $vr_{t,w}$ is the invasive vegetation growth (quantified by a percentage as the area of natural growth of invasive vegetation within a wetland unit divided by the total area of the wetland unit) during time period t in wetland unit w. An area of natural growth can be

defined by the product between a parameter that represents how much invasive vegetation spreads (vs_t) at time period *t*, and the initial coverage of invasive vegetation in wetland unit *w* at the start of the modeling period ($IV_{t=0,w}$). For example, if invasive vegetation spreads 15% per year at a constant growth rate and with respect to an initial invasive vegetation area of 300m^2, and assuming that vegetation spreads over eight months (dormancy period in winter), invasive vegetation spread (*vs*) monthly will be 1.88% (15/8) and the area of natural growth monthly will be 5.6 m^2. Vegetation response *vr* can be affected by different abiotic and biotic factors. Among the most important are the hydrologic factors associated with the magnitude, frequency, timing, and quality of water availability [*Hudon et al.*, 2005]. However, there is not clear-defined interactions among these factors and natural vegetation growth [*Bastlova et al.*, 2004]; thus, we assume a constant growth rate in Equation 3.7 as a first attempt to represent this important interaction.

One management constraint limits invasive vegetation removal by the available financial budget, *b* ($) for the analysis period (Eq. 3.8).

$$\sum_{t,w} RV_{t,w} \cdot ta_w \cdot uc_t \leq b \tag{3.8}$$

Here ta_w (m^2) is the total area of the wetland unit *w*, uc_t ($/m^2) is the unit cost to remove invasive vegetation during time period *t*, and $RV_{t,w}$ is the removal percentage as defined previously.

A second management constraint limits how frequently Refuge staff can adjust gates and water control structures to change water levels from one time period to the next (Eq. 3.9.1 – 3.9.5). This constraint is important because changing water levels in wetland

units requires staff to manually open and close gates in each wetland unit. However, the time and people available to operate gates are limited. We incorporate limits on gate operations in three steps: (i) identify changes in hydrological variables that require wetland staff to open and/or close gates; (ii) define a mathematical function that specifies the water level changes that require gate operations, and (iii) limit the number of gate operations allowed based on the available time and personnel to manipulate gates.

First, we found that managers must open or close gates when changes in water releases from [$x^r_{t,w}$ (ha-m/month)] or deliveries to [$x^d_{t,w}$ (ha-m/month)] a wetland unit over consecutive time periods (Eqs. 3.9.1 and 3.9.2) exceed a threshold change [x_0 (ha-m per time period)]. Changes of releases or deliveries can be positive or negative indicating increasing or decreasing releases or deliveries over time.

$$x^r_{t,w} = \sum_j \left(Q_{t,w,j} - Q_{t-1,w,j} \right), \quad \forall t \geq t_0, w \tag{3.9.1}$$

$$x^d_{t,w} = \sum_j \left(Q_{t,j,w} - Q_{t-1,j,w} \right), \quad \forall t \geq t_0, w \tag{3.9.2}$$

There are three cases of changes that require gate operations: when (i) releases from the wetland unit *w* increase over consecutive time periods *t* and *t-1* faster than the threshold change ($x^r > x_0$); (ii) releases decrease faster than the threshold ($x^r < -x_0$); or (iii) deliveries decrease faster than the threshold ($x^d < -x_0$). Increasing deliveries to a wetland unit do not require manipulating the wetland unit's gates because gate settings at the prior time period can tolerate higher flow at period *t*. We use the variable *x* (without a

superscript) to generically refer to any of the three cases requiring gate manipulation $\left(x_{t,w} \in \left(\left|x_{t,w}^{r}\right| > x_0, x_{t,w}^{d} < -x_0\right), \forall t \geq t_0, w\right)$.

Second, we formulated a smooth yet sharply transitioning sigmoidal function *f* that identifies when changes in releases or deliveries from one time step to the next are sufficiently increasing or decreasing to require managers to manipulate gates (Eq. 3.9.3 and Figure 3.3). This sigmoidal function transitions from zero (no gate change required) to one (gate change required) – or vice versa – in the neighborhood of the change threshold, x_0. We tested numerous alternative approaches to represent the transition including binary variables [*Grossmann et al.*, 2002], logical functions [*Rosenthal*, 2012], non-continuous functions (ratio equations) and exponential smoothing functions, and found the sigmoidal function desirable because it (i) gave smooth and computationally feasibly transitions over large positive or negative changes of releases and deliveries, (ii) allowed us to define a non-zero threshold x_0, and (iii) solved much faster as a non-linear rather than mixed-integer problem.

$$f\left(x, g_u, g_l\right) = \frac{g_u - g_l}{2} \cdot \left[\frac{\tan^{-1}\left(\left(x - x_0\right)/k\right)}{\pi/2} + 1\right] + g_l \qquad (3.9.3)$$

Here, g_u and g_l are asymptotic values that the sigmoidal function approaches when x is, respectively, either above or below the transition value of x_o; k is a curvature parameter where smaller values represent more curvature and a sharper transition from g_l to g_u in the neighborhood of x_o. For gate manipulations, g_l and g_u take values of either 0

or 1 that depend on the direction of the transition. For increasing releases ($x^r > x_0$), g_u=1 and g_l=0, whereas for decreasing releases or deliveries ($x^r < x_0$ or $x^d < x_0$) g_u=0 and g_l=1.

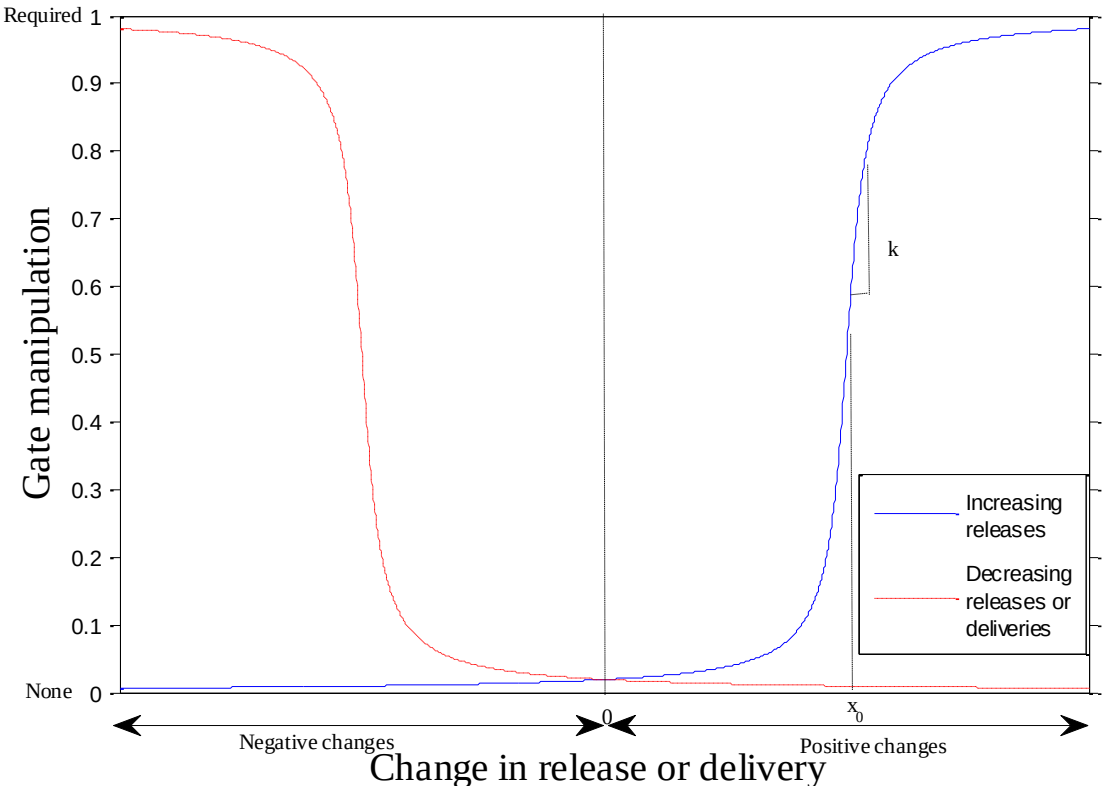

Figure 3.3. Sigmoidal function that relates required gate changes in releases from or deliveries to a wetland unit over successive time steps. The solid blue line covers increasing releases over time and the dashed red line covers decreasing releases or deliveries over time.

These conditions define a set of variables G^{r+}, G^{r-}, and G^{d-} that take the value of 1 (or a value near 1) when a gate change is required to accommodate, respectively, increasing releases, decreasing releases, or decreasing deliveries and a value of 0 (or close to 0) otherwise (Eqs. 3.9.4).

$$G_{t,w}^{r+} = f\left(x_{t,w}^{r},1,0\right);\ G_{t,w}^{r-} = f\left(x_{t,w}^{r},0,1\right);\ G_{t,w}^{d-} = f\left(x_{t,w}^{d},0,1\right) \tag{3.9.4}$$

Third, we constrain the sum of the three *G* variables representing required gate manipulations for the three cases (Eq. 3.9.5) to be less than the parameter ag_t (unitless). The *ag* parameter represents the number of wetland units for which managers can change gates within the time period *t* and is determined based on the available time and staff personal to manipulate gates.

$$\sum_{w}\left(G_{t,w}^{r+}+G_{t,w}^{r-}+G_{t,w}^{d-}\right)\leq ag_t \quad , \quad \forall t \tag{3.9.5}$$

A final set of constraints require the decision variables *S*, *Q*, *WD*, *IV*, *RV*, and *G* to be non-negative. Equation (3.3) subject to constraints (3.4) to (3.9) [base case] comprise non-linear optimization programs that identify the water allocations and vegetation management actions that maximize the weighted usable area for wetlands.

3.2.6. Simulation Capabilities

The model can also simulate wetland performance for prior or specified hydrologic conditions. Simulation is performed by adding Eq. 3.10 to the model to set storage values equal to prior observed or desired storage volumes ($ds_{t',w'}$) at specified times *t'* in wetland units *w'*.

$$S_{t',w'}=ds_{t',w'} \quad , \quad \forall t'\in t, w'\in w \tag{3.10}$$

Managers can also use these simulation capabilities to allocate pre-determined volumes of water to particular wetland units to achieve goals or satisfy constraints that are not already included in the model. For example, a wetland manager can require specific water depths in wetland units to provide recreation (hunting) services (not

already included in the objective function), control avian diseases like botulism (drain and dry affected wetland units and flood units free of the disease), or simulate time-periods when a wetland unit will go offline for maintenance. Managers can also use simulation to quantify wetland performance under past observed hydrological conditions and compare that performance with results from model-recommended water and vegetation management actions.

3.2.7. Input Data, Model and Outputs

The model uses a variety of input data to describe the hydrological, ecological, and management components (Figure 3.4). For the application in this study, these input data were gathered through participatory meetings with managers, review of wetland management plans, and field visits. The connection of wetland units, junctions, and canals was specified using Hydroplatform [*Harou et al.*, 2010]. The optimization model was programmed using the General Algebraic Modeling System (GAMS) software [*Bussieck and Meeraus*, 2004] and solved using the non-linear CONOPT solver [*McCarl et al.*, 2008]. We used Matlab to post-process and graphically display results. Model outputs comprise reports, time series, and maps that show water allocations and vegetation control actions among wetland units that will improve wetland habitat for bird species as well as spatial and temporal wetland habitat performance. Additional sensitivity analysis shows wetland performance for changes in parameters such as water availability, vegetation response, financial budgets, and the time and staff available to manage gates.

Inputs	Outputs
Hydrological • Water availability (Volume time^{-1}) • Network connectivity • Initial, maximum and minimum wetland storage (Volume) • Evaporation loss (length) • Storage, area, and water depth relationships for wetland unit (Volume, area, and length, respectively) • Channel capacities (Volume time^{-1}) **Ecological** • Initial vegetation cover (Percentage) • Priority species (unitless) • Species habitat requirements (unitless) • Species weights (unitless) **Management** • Unit cost of removing invasive vegetation (Currency area^{-1}) • Total financial budget to manage vegetation (Currency time^{-1}) • Number of wetland units at which managers can open/close gates to adjust water levels in a particular time period (unitless)	**Wetland Performance** • Available surface area that provides suitable hydrological and ecological conditions for priority bird species (Area) **Recommend** • Water allocations to wetland units (Volume) • Water depths in wetland units (Height) • Reduction of invasive vegetation (Percentage) • Allocation of financial budget to reduce invasive vegetation (Currency time^{-1}) **Simulate** • Water allocations based on wetland management requirements (Volume) **Shadow Values and Sensitivity Analyses** • How changes in water availability, vegetation response, financial budgets and time available to control gates affect wetland management performance

Figure 3.4. Key model inputs and outputs.

3.3. Model Application

We apply the systems model at the Bear River Migratory Bird Refuge, Utah, which lies at the outlet of the Bear River on the northeast corner of the Great Salt Lake (Figure 3.5). The Refuge covers 118.4 km^2 and includes wetlands that are divided into 25 managed wetland units separated by dikes and supplied water through a series of canals controlled by gates and weirs. This hydraulic infrastructure allows managers to

manipulate water levels in each wetland unit with the main purpose to provide habitat for a wide variety of plants, insects, amphibians, and birds.

Figure 3.5. Location of the Bear River Migratory Bird Refuge in the Bear River basin.

The Refuge typically experiences summer water scarcity from large diversions by upstream irrigators [*Kadlec and Adair*, 1994]. In the future, the Refuge risks losing part or all of its water supply if Bear River water is transferred outside of the basin to support future growth on the Wasatch Front, Utah [*Anderson et al.*, 2004]. In the Refuge, staff adjusts gates and water control structures to allocate water to each wetland unit.

However, limited personnel mean managers try to maintain near-constant water depths in wetland units through the year.

Furthermore, invasive vegetation (*Phragmites*) at the Refuge is reducing plant and animal biodiversity due to aggressive growth and displacement of more desirable plant species. Refuge managers control invasive vegetation by applying herbicides (usually glyphosate, Rodeo) followed by burning to remove dead *Phragmites* [*Olson,* 2007]. Managers want to know how changes in water availability and budget impact wetland units and how they can better allocate scarce water and budget to improve wetland performance.

Data describing the wetland management goal, performance indicators, decision variables, and constraints were identified in participatory meetings with Refuge wetland managers. Our Refuge partners also collaborated to verify the conveyance network for the Refuge entered into our model (Figure 3.6). This network includes: 3 inflows (Bear River, Malad River and Box Elder creek), 25 wetland units, 5 outlets, and 70 junctions. 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, part of the data was obtained from partners at the neighboring Bear River Club. In other cases, we correlated missing gauge records with Bear River flows at the Corinne station.

Using the Refuge Habitat Management Plan [*Olson et al.*, 2004], and meetings with Refuge managers, we identified priority bird species, their habitat requirements, and corresponding habitat suitability curves. Three priority bird species were identified: (i) Black necked stilt *(Himantopus mexicanus),* (ii) American avocet (*Recurvirostra*

americana) and (iii) Tundra swan (*Cygnus columbianus*). Each species has preferences and needs for specific and different water depths (Figure 3.7) at different times of the year (Table 3.1). For example, Black necked stilt prefer shallow water depths between 0.15 and 0.25 m, so *HW* values in this range of water depths are close to 1. The other selected species need medium (0.45 m - 0.55 m) or deep (greater than 0.55 m) water.

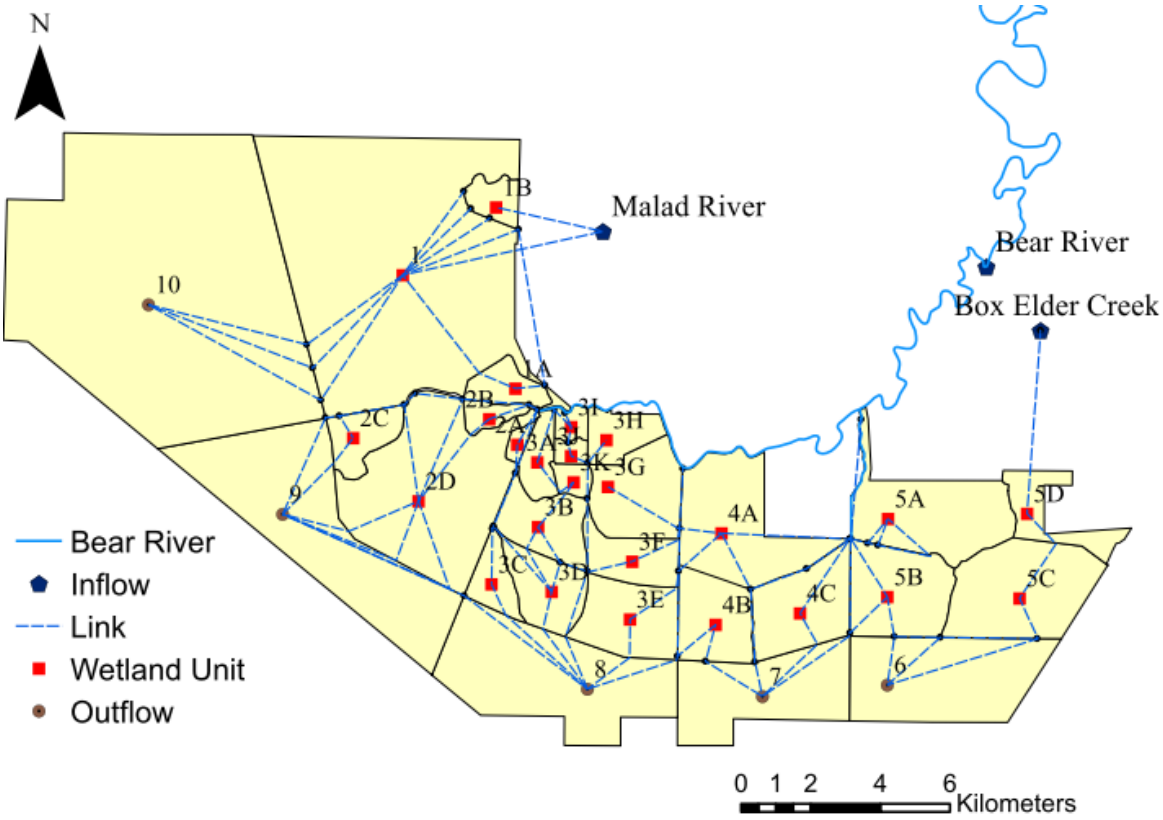

Figure 3.6. Schematic of the network conveyance for the Bear River Migratory Bird Refuge with water inflow locations, 25 actively managed wetland units (units 1A to 5D), conveyance links, and outflows (units 6 to 10).

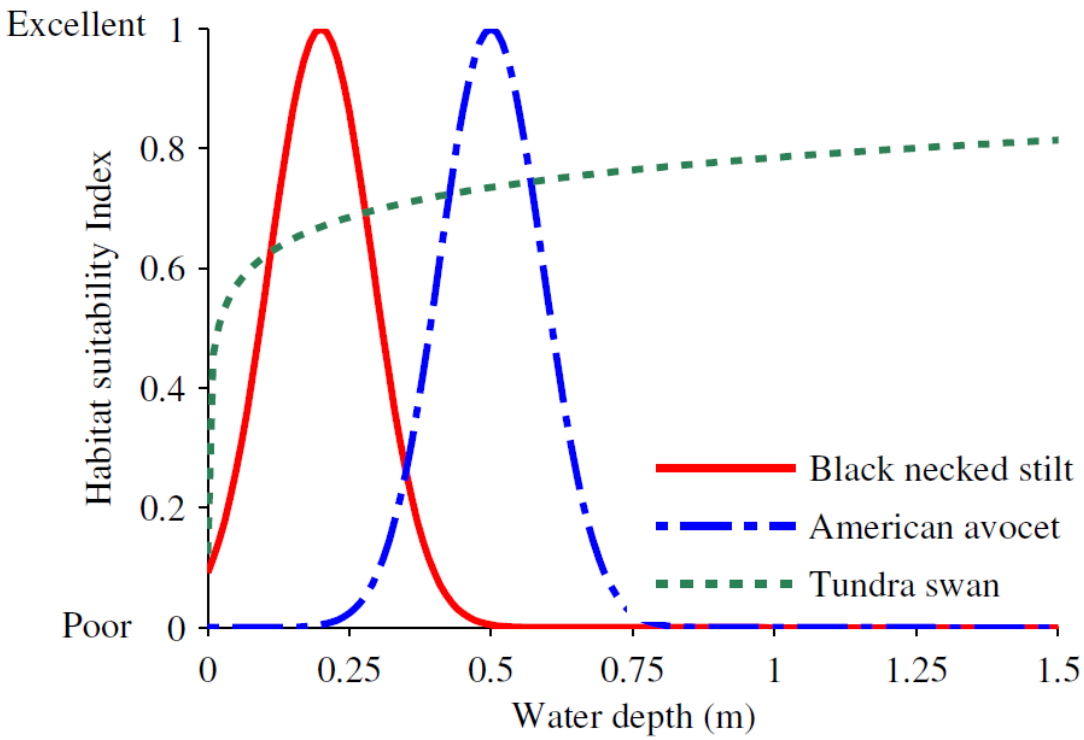

Figure 3.7. Habitat suitability indices for three priority bird species at the Refuge.

We use species weights, *sw*, to prioritize management for a particular species during a month (Table 3.1). For example, American avocet is prioritized from April to September because the Refuge hosts up to 55% of the continental avocet population during this time and avocets use the Refuge to nest, brood, rear hatchlings, and for stopover during migration before departing at the end of September for other wintering grounds [*Olson et al.*, 2004]. Thus, it is important for the Refuge to provide habitat for this bird species from April to September. Similarly, Black-necked stilt arrive in Utah in early April and depart for wintering in September. In contrast, Tundra-swan use the Refuge as a staging area and migratory stopover during the winter months [*Olson et al.*, 2004] and are prioritized during those months.

Table 3.1. Weighting Parameters and Water Depth Preferences 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

Additional model input data were obtained from: (i) Western Regional Climate Center web page (monthly evaporation estimates from http://www.wrcc.dri.edu/); (ii) studies of the Refuge's water requirements [*Christiansen and Low*, 1970; *Kadlec and Adair*, 1994]; (iii) field data collection, including ongoing work to quantify invasive vegetation cover [*Vanderlinder et al.*, 2014]; and (iv) management and field data provided by Refuge staff, including the Refuge operating budget and elevation profiles for Refuge wetland units derived from LiDAR (which we used to estimate water depth-storage-flood area relationships).

We used the input data to define a series of scenarios for the Refuge. A base case scenario considers hydrologic conditions of 2008, existing budget of $180,000/year to reduce invasive vegetation, and only allowed staff to change water levels in four wetland units per month (current Refuge staffing limits). Scenario 1 removed the gate management constraints (Eqs. 3.9.1. - 3.9.5) and allowed staff to change water levels as often as needed. Scenarios 2 and 3 identified the impact of extreme hydrological events on wetland performance considering changes in the magnitude and frequency of flow affecting the reproduction and mortality of wetland plant and animal species in wetlands [*Mitsch and Gosselink*, 1993; *Snodgrass et al.*, 1996]. Scenarios 2 and 3 also allow

managers to change water levels as often as needed and further modified the inflow parameter (parameter *in* - Equation 3.4) to values observed in dry and wet year at the Refuge. Scenarios 4 and 5, instead adjusted the financial budget (parameter *b* - Equation 3.8) to represent, respectively, an increase and decrease in 50% of the current budget to remove invasive vegetation at the Refuge. Finally, in scenarios 6 and 7, we adjusted the parameter *vs* related to vegetation response (Equation 3.7) to represent an increase annually in 15% and 30% of existing invasive vegetation growth with respect to the initial invasive vegetation, respectively. We input the vegetation spread monthly, assuming that invasive vegetation grows constant between April to November (dormancy period in winter). For example, 15% of annual growth of invasive vegetation spread is represented as 1.8% (15/8) of monthly growth. We use an average of 15% and a maximum of 30% of increasing invasive vegetation per year based on previous work [*Hudon et al.*, 2005] and estimation of vegetation growth rate using remote sensing images at the Refuge. This percentage of growth reflects the natural expansions of invasive vegetation over time that are caused by changes in water level, flow duration , and nutrients [*Hudon et al.*, 2005; *Saltonstall and Court Stevenson,* 2007; *Mozdzer and Zieman,* 2010; *Kettenring et al.*, 2011].

3.4. Results

Comparing results from the base case (model recommendation) and previous management shows there are opportunities at the Refuge to increase by threefold the available surface area that provides suitable hydrological and ecological conditions for the three priority bird species. To achieve this increase, the model recommends increasing and more dynamically varying water levels through time in several wetland

units (Figure 3.8, red lines). For example, the model recommends maintaining deeper water in wetland units 1B, 3F, 3J, 4A, 5A, 5D during winter and early spring and shallower water later in the summer. These actions contrast with the near-constant water depths managers maintained throughout 2008 in the same wetland units (Figure 3.8, blue bars).

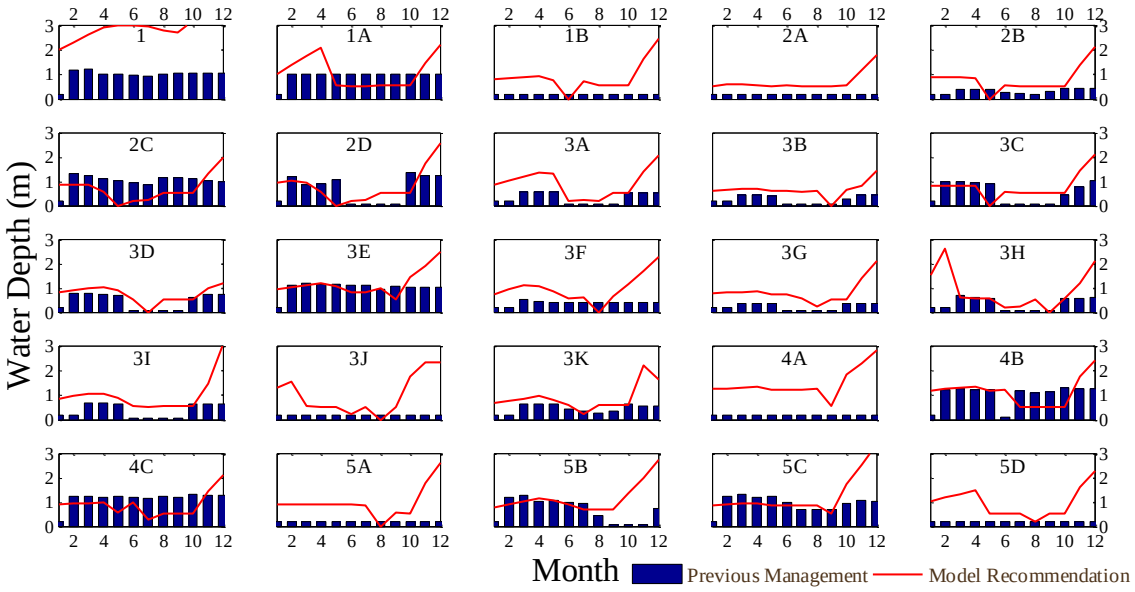

Figure 3.8. Comparison of model recommended (optimized, red line) and previous management (simulated, blue bars) water allocations by month and wetland unit during 2008.

When more dynamically managing water levels according to the optimized results, composite habitat suitability (*HC*) for priority bird species is highest, especially during November to February (Figure 3.9). However there are some units such as 2A that maintain *HC* values greater than 0.5 all year. April through August are particularly critical months with the majority of wetland units showing poor conditions except for units 2A, 3D, and 3J.

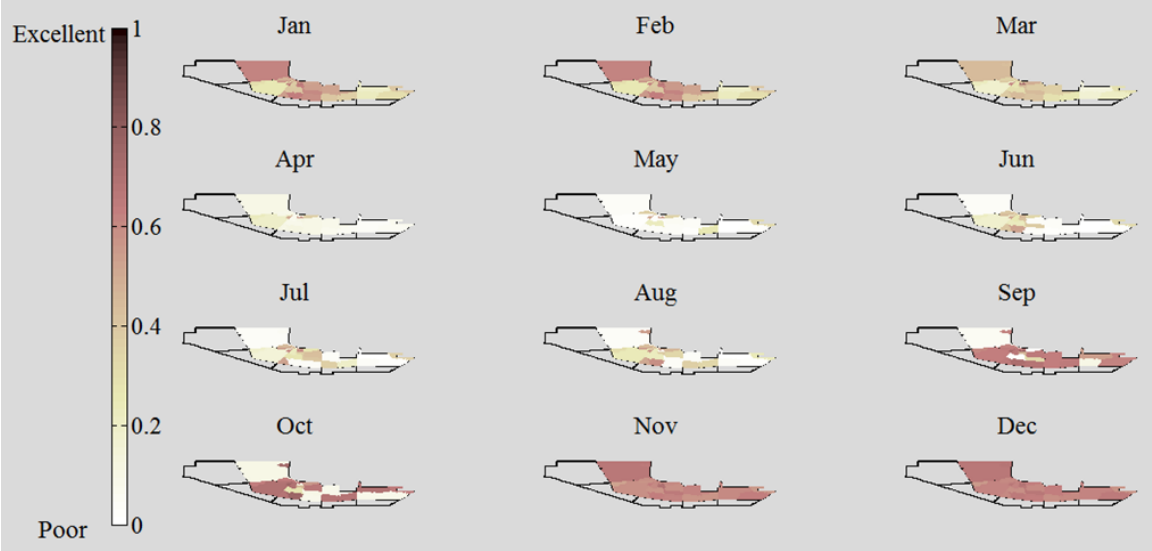

Figure 3.9. Spatial and temporal distribution of composite habitat suitability index *(HC)* for optimized base case in 2008. Dark shading denotes areas with water depths and vegetation cover more suitable for the three priority bird species.

Shadow value (Lagrange multiplier) results also identify how the objective function changes if we relax a model constraint by one unit [*Harou et al.*, 2009]. For the Refuge model, shadow values associated with the equation of water mass balance (Eq. 3.4) identify how changing inflow to the Refuge affects overall wetland performance. For example, increasing Bear River flow by 1 ha-m in July increases the suitable habitat area for key bird species by 21,630 m^2 (Table 3.2). This finding suggests that managers can increase an average depth of 0.46 m across wetland units (10,000/21,630 = 0.46 m). Increasing water depth in wetland units will improve the habitat of birds with medium and deep water depth preferences (e.g., American avocet, Tundra swan). Also, very low shadow values from February to June, August and October show that water availability does not have high impact on the wetland performance, whereas performance can be critically impacted by upstream water abstraction in July and September.

Table 3.2. Shadow Values (Lagrange Multiplier) Associated with the Mass Balance Constraint[a]

Month	Shadow Values (m^2/ha-m)
Jan	5,884
Feb	0
Mar	0
Apr	0
May	0
Jun	0
Jul	21,630
Aug	0
Sep	11,635
Oct	0
Nov	2,234
Dec	795

[a] Shadow values are related to the base case scenario for the Refuge. Values indicate the decrease in the suitable habitat area if water availability is reduced by one unit.

To evaluate how sensitive recommendations are to changes in model inputs, we also compared the 2008 base case (limited gate operation) to 7 scenarios that independently consider changes in allowable gate operations (scenario 1; Table 3.3), water availability (scenarios 2 and 3), financial budget for management (scenarios 4 and 5), and vegetation responses (scenarios 6 and 7).

Installing a system of automatic gates in scenario 1 (i.e., staff can adjust water levels in wetland units as often as they need) improves wetland performance by about 21.7% in comparison to the base case. The dry event (scenario 2) shows that reducing annual water availability by 52% with respect to the automatic gates scenario decreases wetland habitat performance by about 5.7% with respect to scenario 1. The wet event

(scenario 3) shows that increasing water availability by 268% with respect to the automatic gates scenario improves wetland habitat performance by about 6.4%.

Table 3.3. Model Performance for Seven Scenarios

	Scenario	Inputs			Result
		Water Availability (year)	Gate Changes/ month	Budget ($1,000/year)	Weight Usable Area for Wetlands (km^2/year)
	Previous Management	2008	4	180	116
	Model Recommendation (Base Case)	2008	4	180	372
1	Automatic Gates	2008	unlimited	180	452
2	Dry condition	1992	unlimited	180	427
3	Wet condition	1997	unlimited	180	481
4	Increase budget by 50%	2008	unlimited	270	468
5	Decrease budget by 50%	2008	unlimited	90	441
6	Increase vegetation response 15% per year	2008	unlimited	180	450
7	Increase vegetation response 30% per year	2008	unlimited	180	425

Scenarios 4 and 5 show that increasing the financial budget by 50% increases wetland performance by 3.3% whereas decreasing the budget reduces the suitable area of wetland habitat by 2.6%. Scenario 6 shows that increasing the annual invasive vegetation growth (*Phragmites*) rate by 15% can reduce the wetland habitat performance by 0.5%. Scenario 7 shows that increasing *Phragmites* at a rate of 30% can reduce the wetland habitat performance by 6.1%. Together, results from scenarios 1 to 7 show that wetland

performance at the Refuge is much more affected by limited staff time to operate gates, water availability, and changes in vegetation response than by changes in the financial budget to manage and reduce invasive vegetation.

We use further sensitivity analysis to characterize how changes in a wider range of water availabilities affect wetland performance (Figure 3.10). We re-ran scenario 1 substituting in water availabilities from the historical hydrological years 1992 (Dry scenario), 1996, 1997 (Wet scenario), and 2004 to 2011. Results show a non-linear relationship between water availability and wetland performance where performance varies between 481 Km^2 for wet conditions and 427 Km^2 for dry conditions.

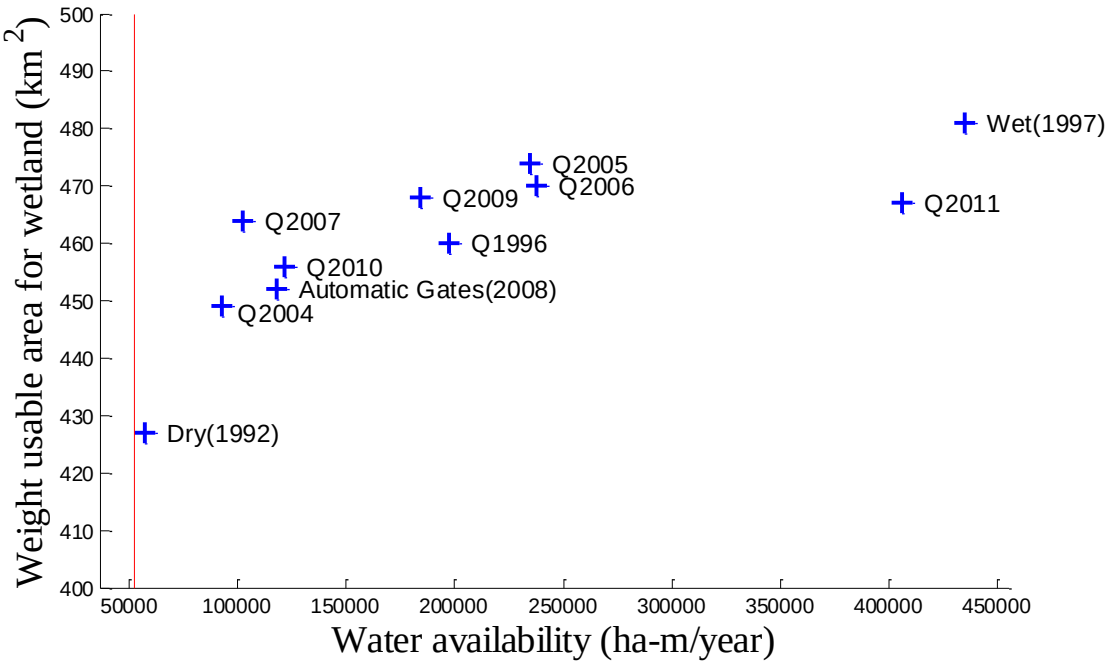

Figure 3.10. Relationship between water availability and weight usable area for wetlands indicator. Blue crosses represent water availability scenarios spanning dry, automatic gates, and wet conditions listed in Table 3.3, as well as flows observed from 2004 to 2011 (Q2004 to Q2011). The red vertical line shows the Refuge's annual water right.

3.5. Discussion

The optimization model recommends water allocation and invasive vegetation control with the objective to maximize the area with suitable habitat conditions for priority bird species. Comparison between the base case scenario of optimized management and past management activities shows that there are opportunities to increase by three-fold the suitable wetland habitat area. To accomplish this, Refuge managers should continue to control invasive vegetation and more dynamically adjust water levels in wetland units through time. For example, by maintaining deeper water in wetland units 1A, 2C, 3A, 3D, 3F, 4B, and 5D during winter and early spring and then decreasing water levels later during the summer (Figure 3.8), managers could increase the suitable wetland habitat area. This behavior will better correspond to the water depth preferences of priority species and with Bear River water availability, which is snow-melt driven and exacerbated by upstream summertime agricultural withdraws.

Although the simulated (previous management) and recommended model uses the same inflow during 2008, the recommended model allocates more water depth in the majority wetland units (e.g., 1, 1B, 2A, 3B, 4A, 5D) than the simulated model. The recommended model takes advantage of all water resources, allocating the available water more efficiently and providing threefold suitable area conditions for bird species (in comparison to the simulated model). The simulated model allocates less water depth over almost all wetland units and, consequently, less wetland habitat performance, even when there is water available to allocate, the simulated model shows dry conditions in some wetland units during June and August (e.g., 1B, 2B, 3D, 3F, and 5A). These results

highlight the capability of the optimization model to use the available water resources to satisfy water depth requirements of priority bird species.

The staff time available to manage gates (scenario 1) is an important factor that affects wetland habitat suitability. This finding highlights that managers should allocate sufficient financial and personnel resources to operate wetland unit gates. Alternatively, the Refuge could benefit by installing an automatic system to control gates that does not require staff to go out to and manually adjust the gates and weirs controlling inflows to and outflows from wetland units.

The evaluation of different hydrologic conditions shows that wetland performance declines rapidly for water availability below 92,539 ha-m/year (Q2004 in Figure 3.10). Since the Refuge's annual water right is approximately 52,000 ha-m /year (Figure 3.10, vertical line), Refuge managers should be concerned about upstream water abstractions that reduce the water available to the Refuge and very concerned if new abstractions infringe on the Refuge's water right. Shadow values associated with the water availability constraint further highlight that July and September are the critical months when reduced water will most impact the wetland performance (Table 3.2).

Currently, the model assumes a linear growth of invasive vegetation in wetland units with respect to time and no vegetation interaction with water level. There are likely additional affects on vegetation from climate, land cover, and anthropogenic disturbance [*Brisson et al.*, 2008]. Future work should address how these disturbances affect invasive vegetation at the Refuge. Remotely sensed images, field work, and controlled experiments can provide the empirical data to further specify these hydrological-plant

response relationships and mathematically represent them in the systems model. We are currently working to include these relationships in the model.

Composite habitat (*HC*) is a key wetland performance metric that is represented by the product of the habitat suitability indices and weighting parameters for particular species. *HC* in the Refuge shows good habitat conditions in almost all wetland unit from September to March and poor habitat conditions from April to August for bird species. This result reflects in part that it is not possible to satisfy all water depth requirements (e.g., shallow, medium, deep) of priority bird species at the same time and in the same wetland unit; that is why the importance of weighting parameters (Table 3.1) to select the preferences of water depth per month. Composite habitat could alternatively be estimated as a geometric mean that implies compensatory relationships between individual suitability indices [*Layher and Maughan*, 1985] or as a minimum composite suitability approach [*Waddle*, 2001]. Further study could help identify how these different methods to aggregate suitability indices to estimate an overall wetland performance influence recommended wetland management actions.

Besides composite habitat estimation, it will also help to further study the effects of including different habitat suitability variables in the calculation of wetland performance. Currently, the model assumes that the main variables that influence the wetland performance in wetlands are water depth and invasive vegetation cover. However, with available input data, we could modify the model to include additional habitat suitability variables such as salinity levels, nutrient levels, substrate cover, and/or temperature. Including these variables requires field data to describe current conditions as well as empirically relate variable values to habitat suitability.

Refuge managers can use the model's simulation features to compare previous management actions (e.g., water level changes) and model's recommendation (optimized conditions). This comparison allows them to identify management actions, such as more dynamically managing water levels, to improve wetlands. Managers can also use the model's simulation capabilities to test how the wetland system will perform under a particular schedule or how to simultaneously reach additional management goals that are outside the scope of the model's objective function. Such goals could include setting specific water depths in particular wetland units to (i) control water bird diseases, or (ii) provide habitat for hunting.

Wetland managers at the Bear River Migratory Bird Refuge participated in the entire process to develop the model from identifying the problem through gathering data and interpreting results. The Refuge staff agreed with the model recommendation regarding that dynamic water level improves the wetland habitat performance. They mentioned the importance to manipulate gates more frequently to allocate appropriate water levels to wetland units and satisfy water requirements of priority bird species. Refuge managers have expressed further interest to use the model and build a more user-friendly model interface so they can use the model in their annual planning to improve wetland habitat. They are also interested to extend the model to (i) incorporate water quality, (ii) expand the number of indicator species, and (iii) investigate preferred water management strategies under shortages or climate change.

3.6. Conclusion

Scarce water resources and invasive vegetation are common problems that affect wetland management for ecosystem functions and services. Wetland managers need

performance metrics that quantify progress towards solving environmental problems such as wetland habitat degradation as well as informed recommendations to improve wetland performance. Here, we quantified and developed a wetland habitat performance metric to embed as an objective function in a system model. The model recommends water allocations and management of invasive vegetation to improve hydro-ecological performance of diked wetlands. Wetland performance is quantified using habitat suitability indices and an indicator defined as weighted usable area in wetlands that represents the surface area available that provides suitable conditions to support species and wetland functions of interest to managers. The optimization model identifies water depths and reduction of invasive vegetation cover in wetland units that managers should undertake to maximize the area with suitable hydrological and ecological conditions for priority bird species. This optimization simultaneously satisfies constraints related to water availability, spatial connectivity, hydraulic capacities, vegetation responses, and available financial resources.

Comparison previous management during 2008 and model recommended management actions for the Bear River Migratory Bird Refuge, Utah, shows that there are opportunities to increase by threefold the suitable habitat area in wetlands. Managers can realize these increases by more dynamically adjusting water levels in wetland units throughout the year. Scenario results also suggest that the performance of wetland habitat is more affected by limited staff time to operate gates and weirs, water availability, and vegetation responses rather than the financial budget to manage invasive vegetation. Upstream water abstractions that impinge on the Refuge's existing water right–particularly during the months of July and September–critically impact wetland

performance. Hence, Refuge managers should protect the Refuge's water right, continue to control invasive vegetation, and allocate water according to model recommendations to reach desired wetland management goals.

The work demonstrates a way to both quantify wetland habitat performance and embed the performance metric in an optimization model that recommends water allocation and invasive vegetation control actions to better achieve the management goals. Future work should identify dynamic vegetation response to water levels through time and extend the wetland performance metric to consider different hydro-ecological variables and ways to mathematically aggregate habitat suitability indices.

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.

$f(x,g_l,g_u)$ = Sigmoidal function that sharply but smoothly transitions from the value g_l to the value g_u when the input x is in the neighborhood of threshold transition point x_0.

g_u ,g_l = Upper (g_u) and lower (g_l) asymptotic values and bounds associated with the sigmoidal function f, unitless.

$G_{t,w}$ = Gate management function that takes the value 1 (or a value close to 1) to indicate changes in releases from or deliveries to a wetland unit require managers to adjust gates or weirs. Otherwise, the function takes a value of 0 (or a value close to 0) to indicate no gate changes are needed, unitless.

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, %.

k = Curvature of the sigmoidal function f that describes the rate of transition from g_l to g_u in the neighborhood of the transition point x_0 , unitless.

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.

$vr_{t,w}$ = 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.

$x^d_{t,w}$ = Change in flow delivery to wetland unit *w* from time period *t* to *t-1*, ha-m/month.

x_o = Transition point where the sigmoidal function *f* smoothly, but sharply, transitions from the lower to upper bound, ha-m/month.

$x^r_{t,w}$ = Change in release from wetland unit *w* from time period *t-1* to *t*, ha-m/month.

References

Ailstock, M. S., C. M. Norman, and J. P. Bushmann (2001), *Common Reed Phragmites australis*: Control and effects upon biodiversity in freshwater nontidal wetlands, *Restoration Ecol.*, *9*(1), 49-59.

Anderson, L., D. Strong, E. Millis, T. Stonely, K. Short, E. Klotz, T. Adams, and E. Edgley (2004), *Utah State Water Plan, Bear River Basin-Planning for the Future.*, Division of Water Resources, Utah.

Bastlova, D., H. Cizkova, M. Bastl, and J. Kvet (2004), Growth of *Lythrum salicaria* and *Phragmites australis* plants originating from a wide geographical area: response to nutrient and water supply, *Global Ecol. Biogeogr.*, *13*(3), 259-271.

Batzer, D., and R. Sharitz (2006), *Ecology of freshwater and estuarine wetlands*, University of California., Oakland, California.

Bolduc, F., and A. D. Afton (2008), Monitoring waterbird abundance in wetlands: The importance of controlling results for variation in water depth, *Ecol. Model.*, *216*(3-4), 402-408.

Brisson, J., É. Paradis, and M.-È. Bellavance (2008), Evidence of Sexual Reproduction in the Invasive Common Reed (*Phragmites australis* subsp. *australis*; Poaceae) in Eastern Canada: A possible consequence of global warming, *Rhodora*, *110*(942), 225-230.

Bussieck, M. R., and A. Meeraus (2004), General algebraic modeling system (GAMS), *Applied Optimization*, *88*, 137-158.

Cardwell, H., H. I. Jager, and M. J. Sale (1996), Designing instream flows to satisfy fish and human water needs, *J. Water Resour. Plann. Manage.*, *122*(5), 356-363.

Chambers, R. M., L. A. Meyerson, and K. Saltonstall (1999), Expansion of *Phragmites australis* into tidal wetlands of North America, *Aquatic Botany*, *64*(3–4), 261-273.

Christiansen, J. E., and J. B. Low (1970), Water requirements of waterfowl marshands in Northern Utah., Utah Division of Fish and Game, Salt Lake City, Utah.

Davis, J., R. Froend, D. Hamilton, P. Horwitz, A. McComb, C. Oldham, and D. Thomas (2001), Environmental Water Requirements to Maintain Wetlands of National and International Importance., Murdoch University, Australia.

Downey, B. A., B. L. Downey, R. W. QuinIan, O. Castelli, V. J. Remesz, and P. F. Jones (2004), MULTISAR: The Milk River Basin Project: Habitat Suitability Models for Selected Wildlife Management Species. *Rep. 86*, 135 pp, Alberta Sustainable Resource Development, Fish & Wildlife, Alberta, Canada.

Fisher, F., and A. Huber-Lee (2005), *Liquid Assets: An Economic Approach for Water Management and Conflict Resolution in the Middle East and Beyond*, 242 pp., Resources for the Future, Washington, D.C.

Grossmann, I. E., J. Viswanathan, A. Vecchietti, R. Raman, and E. Kalvelagen (2002), GAMS/DICOPT: A discrete continuous optimization package, edited, GAMS Development Corporation, Washington D.C.

Hardy, T. B. (2005), *The Theory and Application of the Physical Habitat Simulation System (PHABSIM)*, Utah Water Research Laboratory, Utah State University, Logan.

Harou, J., M. Pulido-Velazquez, D. E. Rosenberg, J. Medellín-Azuara, J. R. Lund, and R. E. Howitt (2009), Hydro-economic models: Concepts, design, applications, and future prospects, *J. Hydrol.*, *375*(3–4), 627-643.

Harou, J., D. Pinte, A. Tilmant, D. E. Rosenberg, D. E. Rheinheimer, K. Hansen, P. M. Reed, A. Reynaud, J. Medellin-Azuara, and M. Pulido-Velazquez (2010), An open-source model platform for water management that links models to a generic user-interface and data-manager, paper presented at International Environmental Modelling and Software Society (iEMSs) Ottawa, Canada.

Herrick, B. M., and A. T. Wolf (2005), Invasive plant species in diked vs. undiked Great Lakes wetlands, *J. Great Lakes Res.*, *31*(3), 277-287.

Higgins, A. J., B. A. Bryan, I. C. Overton, K. Holland, R. E. Lester, D. King, M. Nolan, and J. D. Connor (2011), Integrated modelling of cost-effective siting and operation of flow-control infrastructure for river ecosystem conservation, *Water Resour. Res.*, *47*(5), W05519.

Hof, J. G., and M. Bevers (2002), Spatial Optimization in Ecological Applications, 320 pp., Columbia University Press, New York.

Hudon, C., P. Gagnon, and M. Jean (2005), Hydrological factors controlling the spread of common reed (Phragmites australis) in the St. Lawrence River (Québec, Canada), *Ecoscience*, *12*(3), 347-357.

Johnson, D., W. Lynch, and T. Morrison (1997), Fish communities in a diked Lake Erie wetland and an adjacent undiked area, *Wetlands*, *17*(1), 43-54.

Kadlec, J. A., and S. E. Adair (1994), Evaluation of water requirements for the marshes of the Bear River Delta., Utah State University, Logan.

Kettenring, K. M., M. K. McCormick, H. M. Baron, and D. F. Whigham (2011), Mechanisms of *Phragmites australis* invasion: Feedbacks among genetic diversity, nutrients, and sexual reproduction, *J. Appl. Ecol.*, *48*(5), 1305-1313.

Kusler, J. (2003), *Wetlands and watershed management*, Institute for Wetland Science and Public Policy of the Association of State Wetland Managers.

Layher, W. G., and O. E. Maughan (1985), *Spotted Bass Habitat Evaluation Using an Unweighted Geometric Mean to Determine HSI Values*, paper presented at Proc. Okla. Acad. Sci, Oklahoma.

Loucks, D. P., E. van Beek, J. R. Stedinger, J. P. M. Dijkman, and M. T. Villars (2005), *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*, UNESCO, Paris, France.

McCarl, B., A. Meeraus, P. V. Eijk, M. Bussieck, S. Dirkse, and P. Steacy (2008), *GAMS User Guide*, edited, GAMS Development Corporation, Washington, D.C.

McCulley, E. (2009), *Adaptive Management on the Legacy Nature Preserve*, in Summer Specialty Conference, edited, American Water Resources Association, Snowbird, Utah.

Mirchi, A., D. Watkins, Jr., and K. Madani (2010), Modeling for watershed planning, management, and decision making, in *Watersheds: Management, Restoration and Environmental Impact*, edited by J. C. Vaughn, Nova Science Publishers, Inc., New York.

Mitsch, W. J., and J. G. Gosselink (1993), *Wetlands*, New York.

Mozdzer, T. J., and J. C. Zieman (2010), Ecophysiological differences between genetic lineages facilitate the invasion of non-native *Phragmites australis* in North American Atlantic coast wetlands, *J. Ecol.*, *98*(2), 451-458.

Olson, B. E. (2007), *Phragmites Control Plan, Bear River Migratory Bird Refuge.*, U.S. Fish and Wildlife Service, Brigham City, Utah.

Olson, B. E. (2008), *Annual Habitat Management Plan, Bear River Migratory Bird Refuge.*, U.S. Fish and Wildlife Service, Brigham City, Utah.

Olson, B. E., K. Lindsey, and V. Hirschboeck (2004), *Habitat Management Plan, Bear River Migratory Bird Refuge.*, U.S. Fish and Wildlife Service, Brigham City, Utah.

Payne, T. R. (2003), *The Concept of Weigthed Usable Area as Relative Suitability Index*, paper presented at IFIM Users Workshop, Fort Collins, Colo.

Rosenthal, R. E. (2012), *GAMS - A User's Guide*, GAMS Development Corporation, Washington, D.C.

Saltonstall, K. (2002), Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America, *Proc. National Academy of Sciences*, *99*(4), 2445.

Saltonstall, K., and J. Court Stevenson (2007), The effect of nutrients on seedling growth of native and introduced *Phragmites australis*, *Aquat. Bot.*, *86*(4), 331-336.

Smith, L., N. Euliss, D. Wilcox, and M. Brinson (2008), Application of a geomorphic and temporal perspective to wetland management in North America, *Wetlands*, *28*(3), 563-577.

Snodgrass, J., A. Bryan Jr, R. Lide, and G. Smith (1996), Factors affecting the occurrence and structure of fish assemblages in isolated wetlands of the upper coastal plain, USA, *Can. J. Fish. Aquat. Sci.*, *53*(2), 443-454.

Stralberg, D., D. L. Applegate, S. J. Phillips, M. P. Herzog, N. Nur, and N. Warnock (2009), Optimizing wetland restoration and management for avian communities using a mixed integer programming approach, *Biol. Conserv.*, *142*(1), 94-109.

Taft, O. W., M. A. Colwell, C. R. Isola, and R. J. Safran (2002), Waterbird responses to experimental drawdown: implications for the multispecies management of wetland mosaics, *J. Appl. Ecol.*, *39*(6), 987-1001.

Tarboton, K. C., M. M. Irizarry-Ortiz, D. P. Loucks, S. M. Davis, and J. T. Obeysekera (2004), *Habitat Suitability Indices for Evaluating Water Management Alternatives.*, South Florida Water Management District, West Palm Beach, Florida.

Vanderlinder, M. S., C. M. U. Neale, D. E. Rosenberg, and K. M. Kettenring (2014), Use of remote sensing to assess changes in wetland plant communities over an 18-year period: A case study from the Bear River Migratory Bird Refuge, Great Salt Lake, Utah, *West. N. Am. Nat.*, *74*(1), 33-46.

Vogel, R. M., J. Sieber, S. A. Archfield, M. P. Smith, C. D. Apse, and A. Huber-Lee (2007), Relations among storage, yield, and instream flow, *Water Resour. Res.*, *43*(5).

Waddle, T. (2001), *PHABSIM for Windows User's Manual and Exercises. Rep. 2001-340*, U.S. Geological Survey, 288 pp.

Walters, C., L. Gunderson, and C. Holling (1992), Experimental policies for water management in the Everglades, *Ecol. Appl.*, 189-202.

Zedler, J. B., and S. Kercher (2004), Causes and consequences of invasive plants in wetlands: Opportunities, opportunists, and outcomes, *Crit. Rev. Plant Sci.*, *23*(5), 431-452.

CHAPTER 4

MODELING INVASIVE *PHRAGMITES* SPREAD TO IMPROVE WETLAND MANAGEMENT[3]

Abstract

Invasive vegetation is a common problem for wetland management. Wetland managers spend millions of dollars to control invasive species, yet control is limited by adequate decision making tools. In spite of previous mathematical models that have tried to represent the spread of invasive vegetation, work remains in developing tools that quantify invasive vegetation spread considering the interdependency of time, space, plant life stages, water conditions and financial resources for control. In this study, we develop tools to simulate the spread and control of *Phragmites australis* (common reed), one of the most successful invasive wetland plant species. First, we develop an agent-based model to quantify invasive *Phragmites* spread as a function of water depth and plant life stage. The model is comprised by a set of discrete entities (agents) that represent the invasive plants within a specific grid-cell. These agents have states constituted by the life stage of *Phragmites* growth. Agent states change in time and space according to a set of rules to specify whether *Phragmites* will be present in the cells. Second, we embed the simulated spread patterns in an existing optimization model that allocates water and recommends invasive vegetation control in wetlands. This embedding process allows us to create an improved optimization model that recommends efficient ways to allocate water to reduce invasive *Phragmites* spread and improve wetland performance. Third, we apply the model at the Bear River Migratory Bird Refuge (the Refuge), the largest

[3] Coauthored by David E. Rosenberg and Karin M. Kettenring.

wetland complex on the Great Salt Lake, Utah. Results suggest that: (1) Managing water level according to *Phragmites* life stage can reduce spread; and (2) Refuge managers should focus on complete control of *Phragmites* in specific areas rather than control part of larger areas. Overall, this modeling effort helps quantify *Phragmites* spread spatially and temporally, as well as provides a novel method to embed results of an agent-based model into a system optimization model to make informed decisions to manage scarce resources and control invasive vegetation.

4.1. Introduction

Spread of invasive vegetation is a major problem in wetlands in the U.S. and throughout the world, in part because invasive vegetation reduces plant species diversity, limits habitat for wildlife [*Chambers et al.*, 1999; *Ailstock et al.*, 2001; *Smith et al.*, 2008], blocks waterways (via increased sedimentation) [*Zedler and Kercher*, 2004], and increases fire frequency and intensity [*Mack et al.*, 2000]. Invasive vegetation usually requires intensive control activities such as applying herbicides and burning to reduce its prevalence [*Van Wilgen et al.*, 2000]. These activities require time, staff, and financial resources that are typically limited. Management agencies spend millions of dollars annually to control invasive plants [*Pimentel et al.*, 2005]. Therefore, it is important to understand the main factors that enhance the spread of invasive vegetation to better manage scarce resources.

Mathematical models have become important tools in analyzing vegetation spread. *Fennell et al.* [2012] use a mechanistic model to simulate the spread of invasive plants that primarily propagate in roads and rivers. *Asaeda and Karunaratne* [2000] use a dynamic model that combines regression analysis with plant phenology to simulate

invasive vegetation in a freshwater ecosystem and to understand its growth pattern. *Meyer and Li* [2013] use a system of integral and differential equations to simulate the growth and spatial spread of a plant population.

These models show the importance of the spatial, temporal, and ecological processes to simulate invasive vegetation spread. However, existing models only consider these factors individually and do not explore the critical interdependence of invasive vegetation, hydrologic condition (e.g., water depth), ecological process (e.g., mechanism of spread), and available resources to control vegetation (e.g., water, budget).

Here, we explore this critical interdependence for a common invasive wetland plant, *Phragmites australis* (common reed, hereafter *Phragmites*). *Phragmites* is present on every continent except Antarctica [*Gucker*, 2008] and its distribution and abundance has increased dramatically in North America over the past 150 years [*Saltonstall*, 2002]. Previous research shows *Phragmites* spread is affected by hydrological disturbance [*Weisner and Strand*, 1996, *Chambers et al.*, 2003], mechanism of spread (seeds vs rhizomes) [*Kettenring and Mock*, 2009], life stage (seeds, seedlings, mature plants), as well as other environmental factors [e.g.,*Chambers et al.*, 2003; *Rickey and Anderson*, 2004; *Kettenring et al.*, 2011]. Mature *Phragmites* reproduces and spreads by sexual (seeds) and asexual (rhizomes, stolons) mechanisms [*Norris et al.*, 2002; *Gucker*, 2008]. Hydrological conditions can alter the rate of spread. For example, *Weisner and Strand* [1996] found that shallow water increases the rate of rhizome growth and extended dry periods can prevent seed germination. Also, *Coops and Van Der Velde* [1995] determined that under submerged conditions *Phragmites* seedling can stop its growth. There is a pressing need to quantify invasive *Phragmites* spread and embed these prior research

findings in tools that decision makers can use to identify how to manage scarce water, labor, and financial resources to control *Phragmites* spread.

We address this need with three main contributions. First, we develop an agent-based model [*Railsback and Grimm*, 2011] to quantify *Phragmites* spread in response to water depth and plant life stage (e.g., seeds, seedlings). The model is comprised of discrete entities (agents) that represent invasive plants. These agents have states that represent progressive plant life stages (seeds, seedlings, mature plants). Agents interact with each other and with their environment which includes both: (1) an array of cells, where each cell represents a specific surface area of wetlands and (2) ecologically-relevant water levels (dry, mudflat, deep). Agent states change in time and space according to the interaction with each other and their environment. These interactions are represented by a set of rules. These rules are defined by: (1) probability values that describe the likelihood of agents (*Phragmites*) in a particular life stage being present in a cell given the water level and *Phragmites* presence in the neighboring cells, and (2) threshold parameters that limit transition probability values. *Phragmites* life stages change if the transition probability exceeds a threshold parameter. We repeat the rules' evaluation in time to simulate *Phragmites* spread. Second, we provide a method to embed results from the agent-based model into a previously developed optimization model (see Chapter 3). This previous model recommends water allocation and invasive vegetation removal in diked wetlands, but does not consider the dynamic interaction between invasive vegetation and water level. Here, we extend this model to both: (1) dynamically estimate invasive vegetation response under different hydrologic conditions and (2) leverage this relationship to recommend how to efficiently allocate scarce water and

financial resources that simultaneously control invasive *Phragmites* and create suitable habitat for priority bird species.

We apply the models at the Bear River Migratory Bird Refuge (hereafter, the Refuge), which is the largest wetland complex on the Great Salt Lake, Utah. The Refuge serves as a critical resting and breeding area for several globally-significant populations of migratory birds. The Refuge covers 118.4 km^2 and is divided into 25 managed wetland units each of which is separated by dikes and supplied with water through a series of canals controlled by gates. This hydraulic infrastructure allows managers to manipulate water levels in each wetland unit to provide suitable habitat for wildlife. *Phragmites* is present in all wetland units and in most water delivery canals on the Refuge [*Olson*, 2007]. Currently, Refuge managers start to control invasive vegetation when *Phragmites* covers 10% or more of the wetland unit. They apply herbicides (usually glyphosate, Rodeo) followed by burning to remove dead *Phragmites* [*Olson*, 2007]. Managers have a pressing need to know the main factors that contribute to the spreading of invasive vegetation and how they can better allocate their scarce water and financial resources to improve the wetland management.

The remainder of this chapter is organized as follows. Section 4.2 presents the agent-based model formulation, calibration, and validation. Section 4.3 describes the methodology to embed the agent-based model results into a systems optimization model to create an improved model that recommends water allocations and financial resources to control invasive vegetation in diked wetlands. Sections 4.4 and 4.5 present and discuss the results. Section 4.6 concludes.

4.2. Agent-Based Approach to Model Invasive Vegetation Spread

Agent-Based Models (ABM) have been used to observe how a dynamic system (e.g., spread of invasive vegetation) arises from the interaction between individual components (agents) with their environment [*Railsback and Grimm*, 2011]. The term "agent" is a modeling term and it can represent an individual or group of organisms within a specific area. Agents become an organizational unit or building block of ecological system models [*Grimm and Railsback*, 2005]. ABM have been applied to understand how an ecological system emerges from the interaction of agents and their environment. For example, *Huth and Wissel* [1994] simulate how individual fish changes their swimming direction and velocity according to the position, orientation and velocities of neighbor fishes to show how a group of fish swim in the same direction in a coordinated manner. Also, *Bennett and Tang* [2006] studied the individual elk behavior and the adaptation to their environment (e.g., available forage, snow depth) to investigate the migratory behavior of elk population in Yellowstone National Park. These examples show that complex behaviors and pattern (e.g., fish schools, elk migration) can be simulated from the interaction of individual components with their environment. This bottom-up approach modeling contrasts with traditional mathematical approaches that model from the top-down, assuming that the modeler knows how the system works and replicates that knowledge [*Davis and Nikolic*, 2010].

Here, we develop an Agent-based Model to simulate *Phragmites* Spread (hereafter, AMPS). AMPS simulates how *Phragmites* spreads under different water conditions and through various plant life stages. Agents represent the invasive plants (*Phragmites*) within a spatial grid cell; these agents have specific goals to grow and

reproduce. Agents have states that represent the *Phragmites* life stages (seeds, seedlings, rhizome spread, rhizome/seed spread). Agents interact with each other and their environment. This environment is represented by: (1) an array of cells, where each cell represents a specific surface area of wetland, and (2) ecologically-relevant water level (dry, mudflat or deep water). A set of rules determines how an agent interacts with the environment to grow and spread through time and space. These rules are defined by probabilities and threshold parameters. *Phragmites* grows or spreads if the probability exceeds a threshold parameter.

Agent-based modeling is appropriate to simulate *Phragmites* spread because it allows us to: (1) represent an ecological system in terms of simple units such as invasive plants that interact with their environment according to an adaptive behaviour (e.g., plants can spread into neighboring areas under specific hydrologic conditions) [*Grimm and Railsback*, 2005], (2) represent the different plant life stages from seeds through mature plants, and (3) capture an emergent spatial pattern of invasive vegetation spread as a result of agent interaction [*Grimm and Railsback*, 2005]. Studying these patterns can help better understand invasive plant spread and strategies to manage that spread. Spatial interaction can be tracked across a grid of discrete cells that represent discrete wetland surface areas. We can compare model results with spatial data such as remote sensing images to calibrate and validate agent-based models. Below, we describe the main components of the ABM.

4.2.1 Main Components

AMPS is composed of four main components: agent, agent states, agent's environment (i.e., cells, hydrologic conditions) and spreading rules described further as follows:

4.2.1.1. Agent. Agent represents *Phragmites* plants within a spatial grid cell. Agents have specific goals of growth and spread. Plant growth and spread occur during specific plant states that vary between seeds and mature plants. Agent's states change according to agent interactions with each other and the hydrologic conditions in their environment. These interactions are represented by a set of rules and are further described below.

4.2.1.2. Agent States. These states are represented by four progressive life stages of *Phragmites* growth which we identified with a literature review [*Chambers et al.*, 2003] and mechanistic research on the plant [*Kettenring et al.*, 2015]. The four stages are:

i. Seeds: The period from when seeds land on ground in their final resting spot until they germinate and seedlings emerge.
ii. Seedlings/Ramet: The period from initial seedling or ramet emergence of the plant until plant is able to reproduce asexually via rhizomes and/or stolons.
iii. Rhizomes: The period in which plants can reproduce only asexually by rhizomes and/or stolons in the adjacent neighboring area.
iv. Rhizomes/seeds: Mature plants that can reproduce either sexually by seeds or asexually by rhizomes/stolons.

Agent state changes from one state to the next state every year (Figure 4.1), we selected this time because *Phragmites* is a perennial grass (i.e., reproduction continues

over multiple seasons) [*Hudon et al.*, 2005] and the natural sequence of stages of *Phragmites* to grow and spread over time. For example, rhizomes of *Phragmites* grow actively during late summer and early winter forming underground roots, then each node of the rhizomes can produce a new plant that will remain dormant during winter and produce a new shoot (hereafter, ramet). Even when *Phragmites* life stages can be accelerated or delayed by environmental and genetic factors [*Ekstam et al.*, 1999], we assume a one year time-step as a first attempt to represent the life state changes during time.

4.2.1.3. Environment. We use cells and hydrologic conditions to represent how *Phragmites* agents interact with each other and their environment.

i. Cell. A cell represents a square surface area of wetlands. We selected an area of 10*10 m^2 because this area reduces the computational time during the simulation of the model, in contrast to a higher spatial resolution (e.g., 1 m^2), which increases run-time and demands more computational resources to simulate the individual-based model. Considering this selected cell-area, multiple agents in different life stages can occupy the same cell.

A grid of cells provide the spatial location of *Phragmites* agents to represent (1) asexual reproduction by rhizomes/stolons to their adjacent neighboring cells, and (2) sexual reproduction by seeds distributed in a finite distance from the current cell. We also use the cell grid to calibrate and validate the model by comparing modeled plant cover to classified remote sensed images of vegetation cover.

ii. Hydrological Conditions. These conditions are dry (no evidence of moisture, water table below the soil surface), mudflat (soil saturated with water table at or very near the

soil surface or flooded up to 15 cm of water depth), and deep (wetland flooded to greater than 15 cm) water levels that are ecologically relevant to *Phragmites* spread. This ecologically relevant characteristic is evidenced in previous research, for instance, when deep conditions prevent *Phragmites* germination [*Avers et al.*, 2009], limit seedling growth [*Coops et al.*, 2004] or when mudflat conditions enhance seedling growth [*Mauchamp et al.*, 2001]. We classified these hydrological conditions based on a literature review [*Chambers et al.*, 2003; *Coops et al.*, 2004; *Avers et al.*, 2009] and the capability of remote sensing images to detect standing water in wetlands.

4.2.1.4. Spreading Rules. These rules describe how the agent interacts with its environment to change states through time. To determine if an agent changes from one life stage to another, the model estimates a probability value, and then compares this probability with a threshold parameter. The agent state (plant life stage) changes only if that probability exceeds the threshold parameter.

i. Probability. The probability specifies the likelihood for agents (*Phragmites*) to be present in a cell given the hydrological condition, agent state in the prior time-step, and the number of neighboring cells where agents are present in a reproductive life stage. There are two type of probability rules that correspond to either growth in the current cell or spread to neighboring cells.

a. Probability for Growth. This is the probability where agent's state (plant life stage) changes from one state to the next in the current cell (blue arrows in Figure 4.1). This probability depends on the hydrological condition in the current cell and the agent state in the prior time-step but does not consider the effects of neighbors (Table 4.1). Growth probabilities for seeds and seedlings/ramets state are based on the literature review and

our own experience that seeds germinate well and become seedlings in moist soil conditions and that dry or deep water depth periods prevent seed germination [*Marks et al.*, 1994; *Coops and Van Der Velde*, 1995; *Olson*, 2007].

b. Probability for Spread. This is the probability where agents in rhizome or rhizome/seeds state spawn new agents in a neighboring empty target cell (red arrows in Figure 4.1). This probability depends on: (1) the hydrological conditions in the target cell as well as (2) the hydrologic conditions and state of agents present in the adjacent neighboring cells. Probability values were determined as follows:

First, we identify the central empty cell and its eight immediate neighbors (Moore neighborhood, Figure 4.2A). Second, we identify the combinations of hydrologic conditions in the target cell and each neighboring cell that will most likely lead to spread in the target cell. The likelihood associated with each neighboring cell is expressed as a weight (unitless) that varies in value from 0 (no spread in unfavorable dry or deep conditions) to 1 (maximum spread under the most favorable mudflat conditions) (Figure 4.2.B). These weights are estimated based on the likelihood that *Phragmites* - in rhizome or rhizome/seed state - spread asexually from a neighboring cell to the target cell (Table 4.2). This likelihood represents the probability that ecologically relevant hydrologic conditions (dry, mudflat, deep) enhance or diminish *Phragmites* spread and this can be evidenced when shallow conditions enhance *Phragmites* rhizomes growth or when deep conditions make horizontal rhizomes shorter [*Weisner and Strand*, 1996].

Third, we sum the weights from neighboring cells. This sum of weights represents how infested cells, with invasive plants, influence the growth of new invasive plants in empty adjacent neighbor areas. This is evidenced in the ecology, when *Phragmites*

spreads laterally through rhizomes or stolons, invading adjacent areas and forage for resources (e.g., light, water, nutrients) [*Stoll and Weiner*, 2000; *Ailstock et al.*, 2001]. Sum of weights vary between 0 (minimum influence of infested cells to the target cell) and 8 (maximum influence of infested cells on the target cell).

Fourth, we normalize the sum of weights to a value between 0 and 1 that represents the probability that agents from neighboring cells will spread into a cell that currently does not have invasive vegetation. Finally, we compare the probability with a threshold parameter to determine if spread occurs. The example in Figure 4.2 illustrates the calculation of the spread probability from four neighboring cells with *Phragmites* that have both mudflat (grey cells) and deep (blue cells) water conditions into a target cell with mudflat conditions.

ii. Threshold parameters. Threshold parameters indicate the minimum probability value needed to change from one agent state to any other agent state. These parameters represent exogenous conditions such as soil disturbance that affect the growth and spread of *Phragmites*. Threshold parameter values range between 0 and 1, where low values indicate conditions that are favorable for *Phragmites* spread, whereas high values indicate difficult conditions for *Phragmites* spread. AMPS has five threshold parameters: three parameters correspond to growth in the seed, seedling/ramet and rhizomes states respectively and two threshold parameters correspond to the rhizome and seed reproduction in the rhizomes/seeds state. Threshold parameters are set during calibration, in which we use remote sensing images, image classification, and a parallel coordinate plot to calibrate threshold parameter values so modeled *Phragmites* spread matches observed spread (see section 4.2.3).

Based on the probabilities to change the agent's state and threshold parameters, we can define the set of rules to represent: (1) *Phragmites* growth in the current cell and (2) *Phragmites* spread in the neighboring cells.

iii. Rules for growth. If agents in seed or seedling/ramet states are present in a cell under specific hydrologic conditions and if probability values are higher than the respective threshold parameter, agents change state (i.e., seeds germinate and become seedlings or ramets grow and become rhizomes in the current cell). Otherwise, seeds do not germinate or seedlings/ramets do not grow.

For example, if there is an agent in a seed state with mudflat conditions in a cell, there is a 0.96 likelihood (see Table 4.1 for seeds and mudflat conditions) that the seed germinates and becomes seedling. Comparing this probability to the threshold parameter (assuming a threshold of 0.4), the model will determine that the seed germinates and becomes a seedling in the next time-step. However, if the cell's hydrologic condition changes to dry, the transition probability will be 0.02, lower than the threshold parameter (0.4) and the agent in the seed state will not germinate.

iv. Rules for spread.

a. Asexual spread by rhizomes/stolons. If a current cell without agents has a higher probability value than the respective threshold parameter, then the target cell will be infested with *Phragmites* in ramet state. Otherwise, *Phragmites* does not reproduce in the target cell. The main difference with the rules for growth is that the probability values now consider the presence of agents in neighboring cells in rhizomes and rhizomes/seeds states to asexual spread.

b. Sexual spread by seeds. If agents are present in a cell in the rhizome/seed plant state and the spread probability for the hydrologic condition (Table 4.1) is higher than the respective threshold probability needed for seed spread, agents will spread their seeds to neighboring cells within a certain distance. Otherwise, agents can-not spread seeds.

To define the distance of seed spreading, we assume that there is a greater trend that seeds spread closer to the mother plant, rather than far away. This approach is based on previous research [*He and Mladenoff*, 1999] where seed dispersal is estimated based on the maximum distance of seed spread and a negative exponential distribution that represents the probability that seeds reach a specific distance from the mother plant. This negative exponential function is represented in a two-dimensional plot that shows a high probability (y-axes) that seeds disperse closer distance (x-axes) to the seed source rather than further from the seed source. Even though seeds can spread great distances via wind, animals or water, most studies show that it is more likely that seeds end up very close to the mother plant [*Stoll and Weiner*, 2000].

Table 4.1. Probabilities That *Phragmites* in a Cell Will Change State Based on Hydrologic Condition

Start State	End State	Dry	Mudflat	Deep	Note
Seeds	Seedlings	0.02	0.96	0.02	Growth from seeds to seedlings state
Seedlings/Ramets	Rhizomes	0.06	0.88	0.06	Growth from seedlings/ ramets to rhizomes state
Rhizomes/seeds	Seeds	0.14	0.57	0.29	Spread from rhizomes/seeds to seeds state

Table 4.2. Likelihood that *Phragmites* in a Specific Plant State will Spread Asexually from a Neighboring Cell to the Target Cell Based on Hydrologic Conditions

Plant State	Dry	Mudflat	Deep
Rhizomes	0.13	0.50	0.37
Rhizomes/seeds	0.14	0.57	0.29

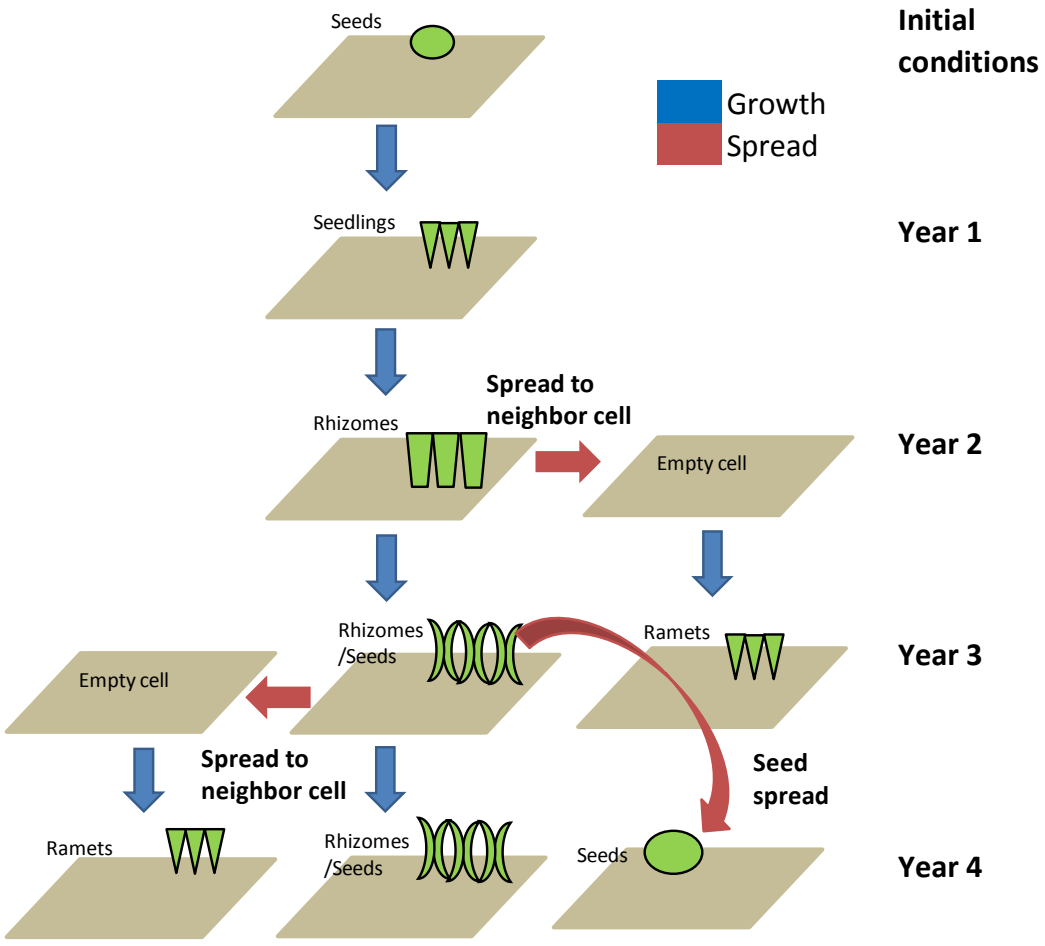

Figure 4.1. Progressive plant states during a period of four years. AMPS simulates the process of growing and spreading of *Phragmites* simultaneously.

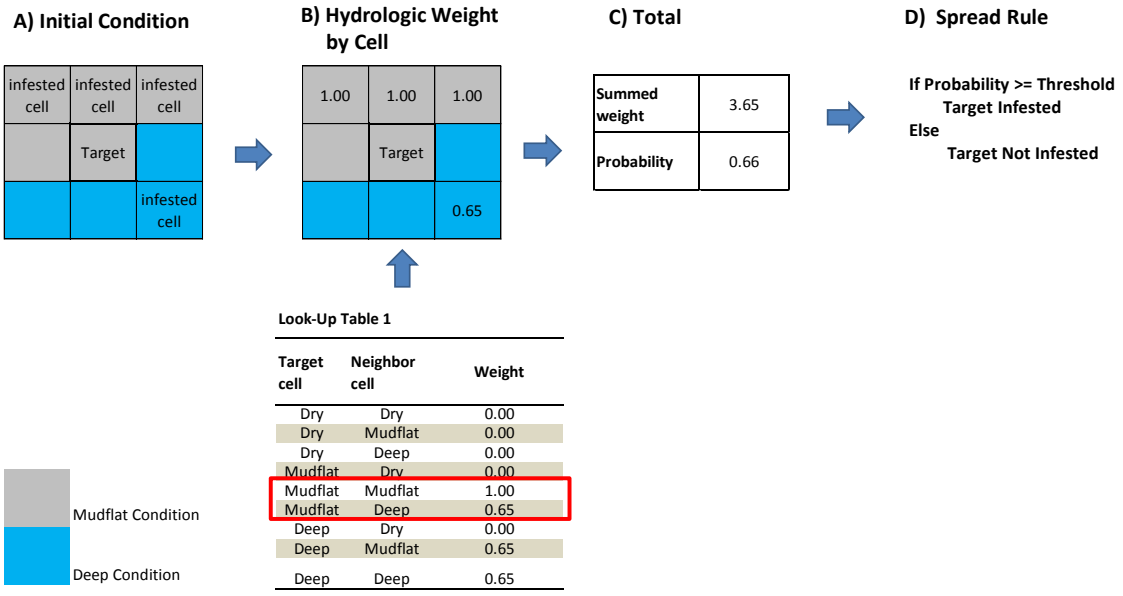

Figure 4.2. Modeling asexual spread of *Phragmites* (agents) from infested neighboring cells to a target cell. A. Example of how a target cell (a cell without agents) is influenced by hydrologic conditions - mudflat (gray cells) and deep (blue cells) - as well as by the number of infested cells (four cells with agents in rhizomes or rhizomes/seeds state). Combinations of hydrologic conditions in the target cell and each neighboring cell are expressed as a weight (Look-up Table 1). B. Each infested cell is labeled with their respective weight. C. Probability of a target cell is estimated as the sum of hydrologic weight in the infested cell. Sum of weights are normalized to determine the final probability. D. Probability value is compared with the threshold parameter to determine if the target cell is infested with invasive plants or not.

4.2.2. Implementation

AMPS uses as input data: (1) probability values to estimate how ecologically relevant dry, mudflat, and deep water conditions alter *Phragmites* spread, (2) the model's parameters (e.g., threshold, seed spread distance), (3) observed water levels in wetland units, and (4) initial area of invasive vegetation. These data were obtained through literature review, expert opinion, GLOVIS web page (Landsat images from http://glovis.usgs.gov/), participatory meetings with wetland managers, field data collection, and model calibration.

The model was implemented in NetLogo [*Tisue and Wilensky*, 2004]. In addition, Matlab scripts were developed to make a supervised classification of Landsat images and determine observed vegetation cover and flooded areas for wetlands at the Bear River Migratory Bird Refuge (Utah). These images were used in AMPS to: (1) specify initial vegetation condition as starting conditions for the model, (2) calibrate the threshold parameter and seed spread distance, and (3) validate AMPS model predictions of vegetation spread.

NetLogo includes a friendly graphical interface that lets users input the initial condition of invasive vegetation, run the model and visualize the vegetation spread without needing to learn details of the programming language. Outputs of the model include reports and plots that help users to: (1) quantify invasive vegetation spread, (2) identify the vegetation spread patterns under different hydrologic conditions, plant life stages, and (3) explore management strategies to control invasive vegetation.

4.2.3. Calibration and Validation Using Remote Sensing Images and Parallel Coordinates

Threshold parameters and seed spread distance are calibrated in the AMPS model to make the invasive vegetation spread estimated by the AMPS simulation better match the observed spread of vegetation identified from classifying remote sensed images taken at the Bear River Migratory Bird Refuge (the Refuge) between 2007 and 2011. The model was calibrated in wetland unit 5C and validated in wetland unit 5B. We selected these wetland units because of the availability of Landsat images and ground truthing points. Here, we describe in more detail the five main steps of the model calibration and validation:

i. We used remote sensing Landsat images and ground points to implement a supervised image classification of vegetation cover and flooded areas. Landsat images, which have been used extensively to map wetlands [*Johnston and Barson*, 1993] and monitor invasive vegetation [*Bernthal and Willis*, 2004], were collected for the Refuge area over the period 2007 and 2011. Also, we used 582 ground truth points collected at the Refuge in 2009, 2010 [*Vanderlinder et al.*, 2014] and 2011 [*Long*, 2012]. The ground truth points included water depth measurements and type of vegetation data collected in situ at the Refuge.

ii. We developed a Matlab script to perform a supervised classification of Landsat images and estimated vegetation cover and flooded areas for the specific wetland unit in 2007-2011. We found there was 73.4 percent agreement between Landsat classification and ground data as a result of a conventional V-fold cross validation [*Hastie et al.*, 2009].

iii. We defined two model performance metrics to evaluate how well the AMPS estimate of invasive vegetation spread matched observed spread. The first metric is the model precision, which we define as the percentage of pixels where Landsat image classification and the AMPS simulation both agree that there is *Phragmites*. The second performance metric is the difference in vegetation response defined as the complementary difference between the invasive plant spread simulated by AMPS for the period of July 2007 to July 2011 and the invasive plant spread observed on the classified Landsat images for the same period. For example, if results of the AMPS simulation show an invasive vegetation spread of 18% (with respect to the initial condition in July 2007) and invasive plant spread observed on the classified Landsat images is 14% at the end of July 2011; the difference in vegetation response will be 96% (100-[18-14] = 96). To improve the

performance metrics, we adjusted three model parameters used to determine: (1) *Phragmites* spread during the rhizome state, (2) *Phragmites* spread during rhizomes/seed state, and (3) seed distance spread during rhizomes/seed state.

iv. Calibration consisted of adjusting the three parameters to identify values that simultaneously maximized both precision and difference in vegetation response. We performed 24 trials, where each trial involved adjusting the three parameters, running AMPS, and calculating the two performance metrics identified in the previous step. We plotted results from the 24 calibration trials in parallel coordinates [Inselberg, 2009] with two axes for the performance metrics and three axes for the calibrated parameters. We found that the lines between the axes for the two performance metrics all cross (Figure 4.3); this crossing indicates that these two metrics are inversely correlated (i.e., an improvement in one performance implies a decrease in the other). Thus, to select the adequate parameters, we filter on the calibration parameters and identify the ranges of those parameters that give stable precision and difference in vegetation response (i.e., changes in threshold parameters will have small effects in the performance metrics) (Figure 4.4). Among eight alternatives selected in Figure 4.4, we selected the blue line as it represents calibration settings that are insensitive to small changes in the parameter values.

v. We validate the AMPS using the threshold parameter values identified in the calibration process and simulate the invasive vegetation spread in a second Refuge wetland unit (5B) during July 2007 to July 2011 (Figure 4.5 A and B). Figure 4.5 C shows the Landsat classified image for the same time.

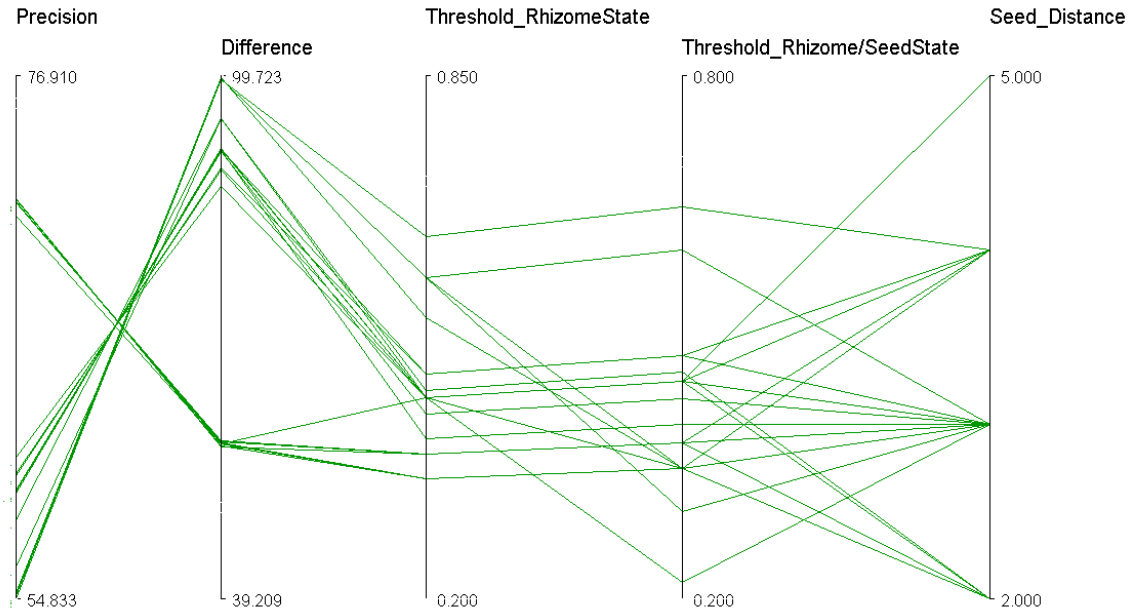

Figure 4.3. Parallel coordinates provide the visualization of 24 trials (green lines), two performance metrics (first two left axes) and three parameters to calibrate AMPS.

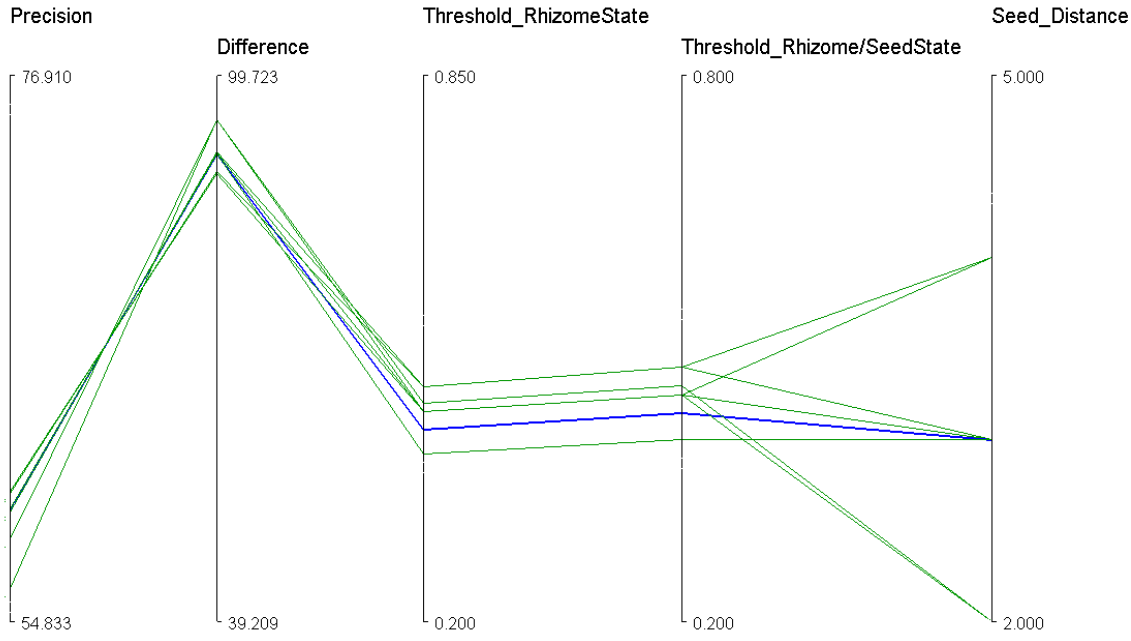

Figure 4.4. Potential alternatives to select the calibration parameters of AMPS using parallel coordinates. The blue line shows the alternative selected that represents the parameters which give the most stable model performance.

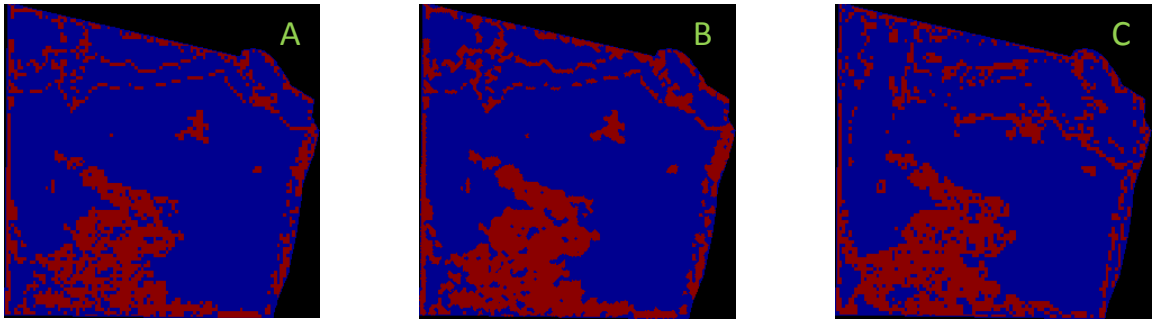

Figure 4.5. Comparison of AMPS model output with Landsat images in wetland unit 5B at the Refuge for validation of the model. A. Before simulation (based on Landsat images) - 2007, B. After AMPS simulation - 2011, C. Landsat classified image - 2011.

We compare results between simulation output and Landsat classification for the calibration (Figure 4.6A) and validation (Figure 4.6B) of wetland units. Red cells show pixels where Landsat and the simulation model both agree that there is *Phragmites*. For the precision, the calibration and validation were 59.4% and 67.2%, respectively, while for the difference in vegetation response, the calibration and validation were 91.0% and 97.9%, respectively.

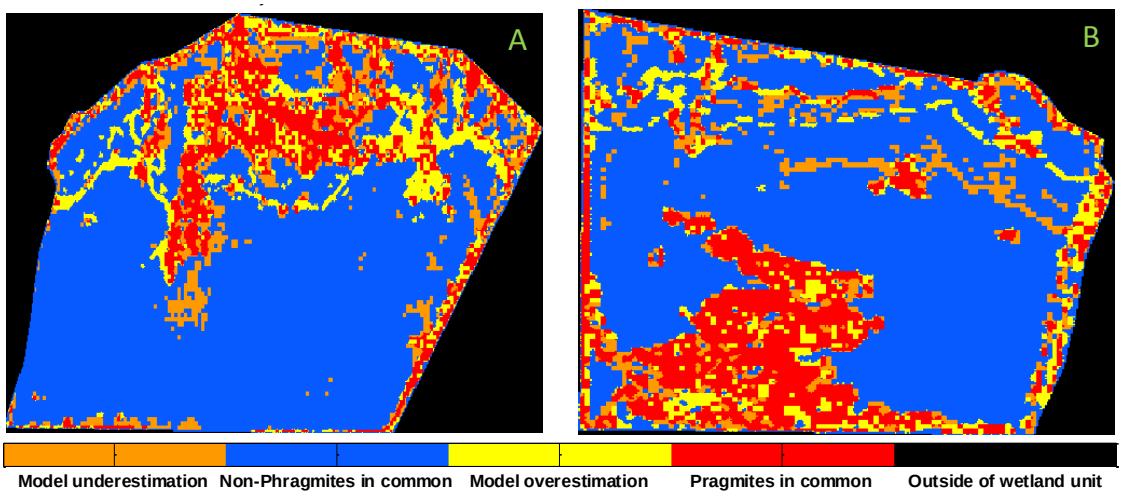

Figure 4.6. Comparison between Landsat classified image and AMPS simulation in 2011. A. Calibration in unit 5C at the Refuge and B. Validation in unit 5B at the Refuge.

Both performances increase for the validation because wetland unit 5B had more ground truth points than wetland unit 5C and, consequently, better performance in the supervised classification of the initial condition of invasive vegetation, which are also used as AMPS model inputs.

4.3. Embedding AMPS Results into Existing Optimization Model

We embed the results and emergent patterns from the agent-based model (AMPS) into an existing system optimization model (see Chapter 3) to investigate how water levels affect invasive vegetation response over time and how managers can allocate water in diked wetland units to control invasive vegetation and increase wetland habitat performance.

4.3.1. Existing Optimization Model

We previously developed a Systems model in Wetlands to Allocate water and Manage Plant Spread (hereafter, SWAMPS) (see Chapter 3). SWAMPS is an optimization model that recommends water allocations and invasive plant control to improve hydro-ecological performance of diked wetlands. The SWAMPS model maximizes an ecological objective defined as the weighted usable area for wetlands (*WU*) which represents the available surface area that provides suitable hydrological and ecological conditions for priority bird species. Model recommendations are subject to constraints like water availability, spatial connectivity of wetlands units, hydraulic infrastructure capacities, vegetation growth, and responses to management, plus resources limitation to manage invasive vegetation and water. SWAMPS was used in 25 wetlands units at the Bear River Migratory Birds Refuge to recommend water allocation and

vegetation management and improve wetland habitat performance for priority birds species on a monthly time-step. SWAMPS results at the Refuge showed that wetland managers can triple the area of suitable-quality habitat by more dynamically managing water levels (for details, see Chapter 3).

One limitation of SWAMPS was an assumption of linear invasive vegetation growth over time and that growth is independent of the hydrologic condition and vegetation life stage. Here, we improve SWAMPS by embedding results of AMPS that dynamically estimate vegetation response to changes in water levels. We term the pre-existing optimization model as "SWAMPS-Linear Vegetation" and the improved optimization model as "SWAMPS-Dynamic Vegetation." Our purpose with the embedding process is to create an improved model (SWAMPS-Dynamic Vegetation) that (1) simultaneously reduces invasive vegetation cover and satisfies wetland habitat requirements; and (2) provides a more realistic estimation of vegetation response to dynamic water changes and over plant life stages rather than assumes that invasive vegetation grow constant over time (SWAMPS-Linear Vegetation).

4.3.2. Embedding Methodology

In order to create SWAMPS-Dynamic Vegetation, we use AMPS and SWAMPS-Linear Vegetation models which have different spatial and temporal characteristics. For example, AMPS is a simulation model that uses a spatial unit of 10*10 m^2, a one year time-step with a multiyear runtime period and discrete water depth conditions (dry, mudflat, deep); while SWAMPS-Linear Vegetation is an optimization model that works for wetland units between 51 ha and 4614 ha at the Refuge, monthly time-step, one year runtime period and continuous water depths.

We develop the following methodology to cross temporal and spatial scales and to transfer data from the agent-based model AMPS to the optimization model (SWAMPS):

a. We use AMPS simulation to quantify *Phragmites* cover and spread over time under three different ecologically-relevant hydrologic conditions (dry, mudflat, deep) and through four life plant stages growth (seeds, seedling/ramet, rhizomes, rhizome/seed states; Figure 4.7a). Simulation spans the 4-year growth period of *Phragmites* from seeds to mature plants. We also refer to this period of four years as a cycle.

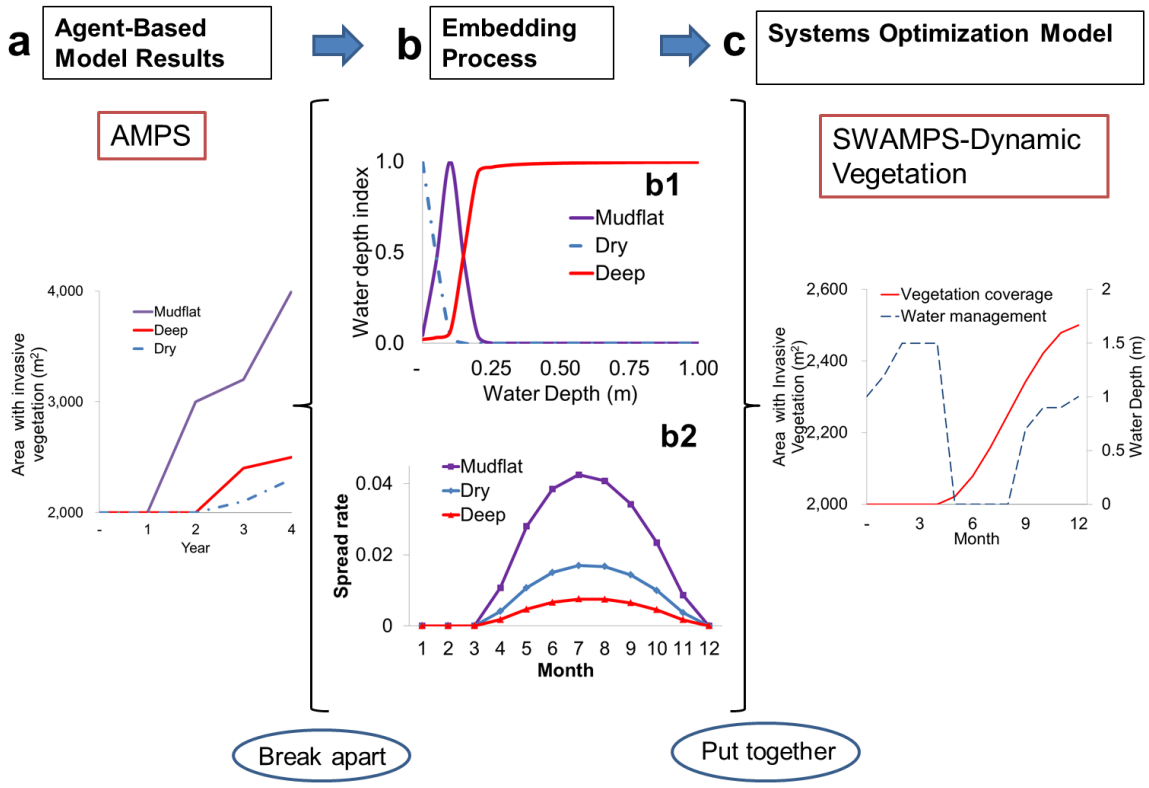

Figure 4.7. Main steps to embed the agent-based model (AMPS) results into the systems optimization model (SWAMPS) that considers dynamic vegetation spread as a function of water depth conditions and life *Phragmites* stages.

b. We identify two main features from the spread curves generated in section "a". The first feature is that water depth affects the spread area of invasive vegetation. To embed

AMPS results into SWAMPS model, we need to convert from water depth categories used in AMPS to continuous water depths used in SWAMPS. We developed a hydrologic classification function to classify water depth data from discrete to continuous water depth – or vice versa. The hydrologic classification functions are three smooth curves that classify water depth categories (dry, mudflat and deep) based on continuous water depth and an index parameter (Figure 4.7. b1). This index parameter takes values in the range between 1 and 0, where values equal or close to 1 are classified to specified water depth category (dry, mudflat, deep); 0 otherwise. For example, for a continuous water depth of 0.25 m (x-axes –Figure 4.7. b1), we will have a water depth index close to 1 for the curve in deep condition, but a water depth index close to 0 for the curve in dry and mudflat condition (y-axes - Figure 4.7. b1). Water depth index is assigned at each time period *t*, location *i*, and for each water depth category *h* (dry, mudflat, deep), and is a function of water depth (wd_i) which is itself a function of storage ($S_{t,i}$) of a wetland unit (Eq. 4.1).

$$hydrologic\ classification_{t,i,h} = fa_h\left[wd_i\left(S_{t,i}\right)\right] , \quad \forall t,i,h \tag{4.1}$$

where fa_h is the hydrologic classification function that relates water depth to the index value.

The second feature that we identified from spread curves (section "a") is that *Phragmites* spread rate changes through time and plant life stage according to the hydrologic conditions. From the AMPS annual invasive vegetation cover results, we interpolate monthly cover values to match the time-step of SWAMPS. Interpolation was performed during the months of invasive vegetation spread (April to November), assuming a dormancy period during winter months (Figure 4.7 b2). Then, we select the

initial conditions of life stage in the optimization model. Finally, we calculate the spread rate (m^2/m^2 month) defined in the Equation 4.2 and for each time *t* and water depth category *h*.

$$spread\ rate_{t,h} = \left(\frac{area_{t,h} - area_{t-1,h}}{area_{t-1,h}} \right), \quad \forall t,h \tag{4.2}$$

where $area_{t,h}$ is the cover area of invasive vegetation in time *t* and water depth category *h*. This invasive vegetation area is simulated in AMPS to estimate the spread rate of invasive vegetation over time and for each water depth category (dry, mudflat, deep). Then, spread rates are combined with the total area of wetland unit (*ta*), percentage of previous invasive vegetation, and water depth category to quantify the invasive vegetation response to changes in water level (Equation 4.3). Together, vegetation response in Equation 4.3 allows us to estimate how much an initial area of invasive vegetation can spread under different water level conditions for each month and for a particular wetland unit.

$$VR_{t,i} = \frac{ta_i \cdot IV_{t-1,i} \cdot \sum_h \left(\left(hydrologic\ classification_{t,i,h} \right) \cdot \left(spread\ rate_{t,h} \right) \right)}{\sum_h \left(hydrologic\ classification_{t,i,h} \right)}, \quad \forall t,i \tag{4.3}$$

where $VR_{t,i}$ (m^2) is the invasive vegetation growth during time period *t* in wetland unit *i*, ta_i is the total area in wetland unit *i*, and $IV_{t-1,i}$ is the invasive vegetation cover (expressed as percentages of the wetland unit area) during previous time period *t* in wetland unit *i*.

c. Substituting Equation 4.3 into the vegetation response constraint in the previous optimization model (SWAMPS- Linear Vegetation, Eq.3.7, Chapter 3) gives the dynamic

vegetation response (Equation 4.4). Here, vegetation response is expressed as percentage of the wetland unit area (i.e., we divide by the total area *ta*) and is expressed in square brackets in Equation 4.4, which determines the cover of invasive vegetation in a monthly time-step and for a specific wetland unit.

$$IV_{t,i} = IV_{t-1,i} + \left[\frac{IV_{t-1,i} \cdot \sum_{h} \left(\left(hydrologic\ classification_{t,i,h} \right) \cdot \left(spread\ rate_{t,h} \right) \right)}{\sum_{h} \left(hydrologic\ classification_{t,i,h} \right)} \right] - RV_{t,i}, \quad \forall t,i \quad (4.4)$$

where $RV_{t,i}$ is the invasive vegetation that managers remove in a wetland unit i in time t. RV is constrained by the available budget to remove invasive vegetation.

Overall, Equation 4.4 incorporates the dynamic interaction considering previous invasive vegetation, water level conditions, spread rate of invasive vegetation, and removed invasive vegetation. Using this dynamic relationship allows managers to make informed decisions about invasive vegetation control considering different wetland management components (e.g., water allocation, budget) simultaneously. The full formulation of the SWAMPS-Dynamic Vegetation model is presented in Appendix 4.1.

4.3.3. Use of SWAMPS-Dynamic Vegetation Response

The SWAMPS model includes input data related to water infrastructure of wetlands, water availability, ecological priority species requirements as well as budget to remove invasive vegetation in wetlands. The model has a montly time-step and runs over one year. The model was coded using the General Algebraic Modeling System (GAMS) software [*Bussieck and Meeraus*, 2004], and solved as a non-linear program using CONOPT [*McCarl et al.*, 2008]. We use Matlab to post process and graphically display results. These outputs include reports that help answer important questions to the wetland

manager such as: How much water is necessary to satisfy wetland-bird habitat requirements and reduce invasive vegetation spread simultaneously? Which wetland units should be prioritized to control invasive vegetation? When should vegetation control be implemented? And what water depth is the most recommendable to control invasive vegetation spread?

4.4. Results

4.4.1. The AMPS Tool

4.4.1.1. Spatial and Temporal Model Capabilities

The calibrated and verified AMPS model simulates spatial and temporal spread of *Phragmites* (Figure 4.8). Users can define initial conditions of *Phragmites* (i.e., agents in their respective cell and under specific hydrologic conditions) and quantify *Phragmites* spread as well as observe the pattern of spread over a specific time of simulation. For example, assuming an initial conditions of *Phragmites* area with 40 infested cells (4000 m^2 in Figure 4.8A) and four years of static mudflat water conditions, AMPS shows that *Phragmites* can spread to neighboring areas and spawn new plants that mature to the rhizomes and rhizomes/seeds (pink and red cells in Figure 4.8B). This spread covers an area of 8400 m^2 that is 2.1-fold larger than the initial conditions.

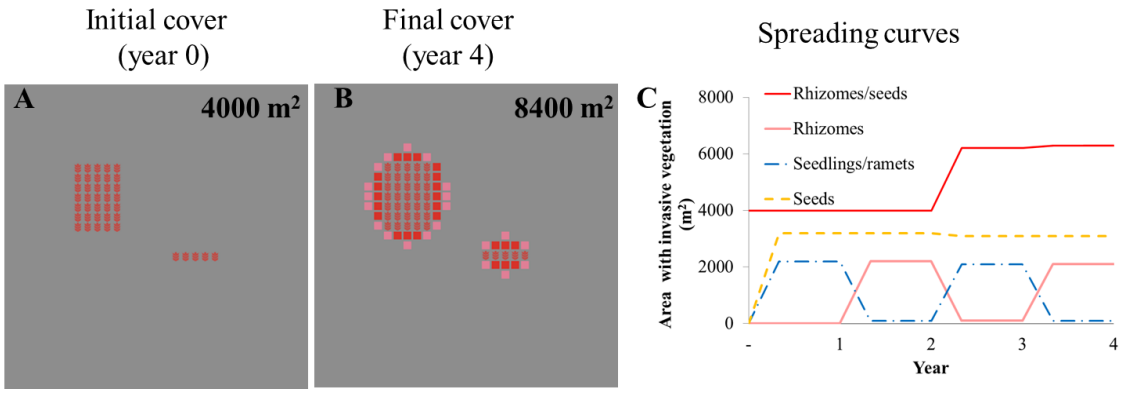

Figure 4.8. Simulation of *Phragmites* spread cover area over time under static mudflat water conditions. A: Initial cover of *Phragmites* in rhizomes/seeds state (red agents), B: After four years, *Phragmites* present in the rhizome state (pink agents) and rhizomes/seeds state (red agents), C: Plants spread through time over four years of simulation.

AMPS simulation also allows us to explore the pattern of *Phragmites* spread over time (Figure 4.8C). Using this pattern, we can identify changes in the *Phragmites* life stages during the years of simulation. For example, in the first year, mature *Phragmites* (red line) reproduces sexually by dispersing seeds (yellow line). The plants can also reproduce asexually be rhizomes/stolons that spread to neighborhood cells and span new seedling/ramet plants (blue line); then, after one year and favorable hydrologic conditions, seeds germinate and continue reproducing; seedling/ramet become plants that are able to reproduce by rhizomes through their neighbors (pink line). Later, rhizomes become mature *Phragmites* plants that are able to reproduce by seeds and by rhizomes.

AMPS shows that the spread area of *Phragmites* in the rhizomes/seed state increases irregularly over the time and plant life stages (Figure 4.8C). For example, after the second year, the spreading curve for *Phragmites* in the rhizomes/seeds states increases by 2200 m^2 due to the maturation of seedlings and spread of *Phragmites* to their

neighborhood. Then in the third year, *Phragmites* spreads only 100 m^2 because plants are in early stage (i.e., seedlings) and are not yet able to spread to neighboring areas.

4.4.1.2. Use of the AMPS to Determine the Effect of Hydrological Conditions on *Phragmites* Spread

AMPS simulates invasive vegetation spread over time in response to different static hydrological conditions (dry, mudflat, deep). Results over 12 years of simulation show that mature *Phragmites* cover triples, doubles, and nearly doubles from an initial cover of 2000 m^2 when water levels are held at, respectively, mudflat, deep, and dry levels (Figure 4.9). Simulation results also show that it is possible to reduce the spread of *Phragmites* by applying or withholding water levels over the 12 years of simulation. These water levels include dry or deep water conditions during the four life stages of *Phragmites* (avoid mudflat conditions) (red line, Figure 4.9). Also, the spread rate increases over the 12 years of simulation (e.g., the slope for mudflat conditions gets steeper during later years) (Figure 4.9). For example, in the 3rd year along the curve of mudflat water condition, cover increases by 800 m^2, while at the end of 9th year, cover increases by 1200 m^2. This result reflects that *Phragmites* area increases over time due to the growth and spread of *Phragmites* from neighboring infested areas.

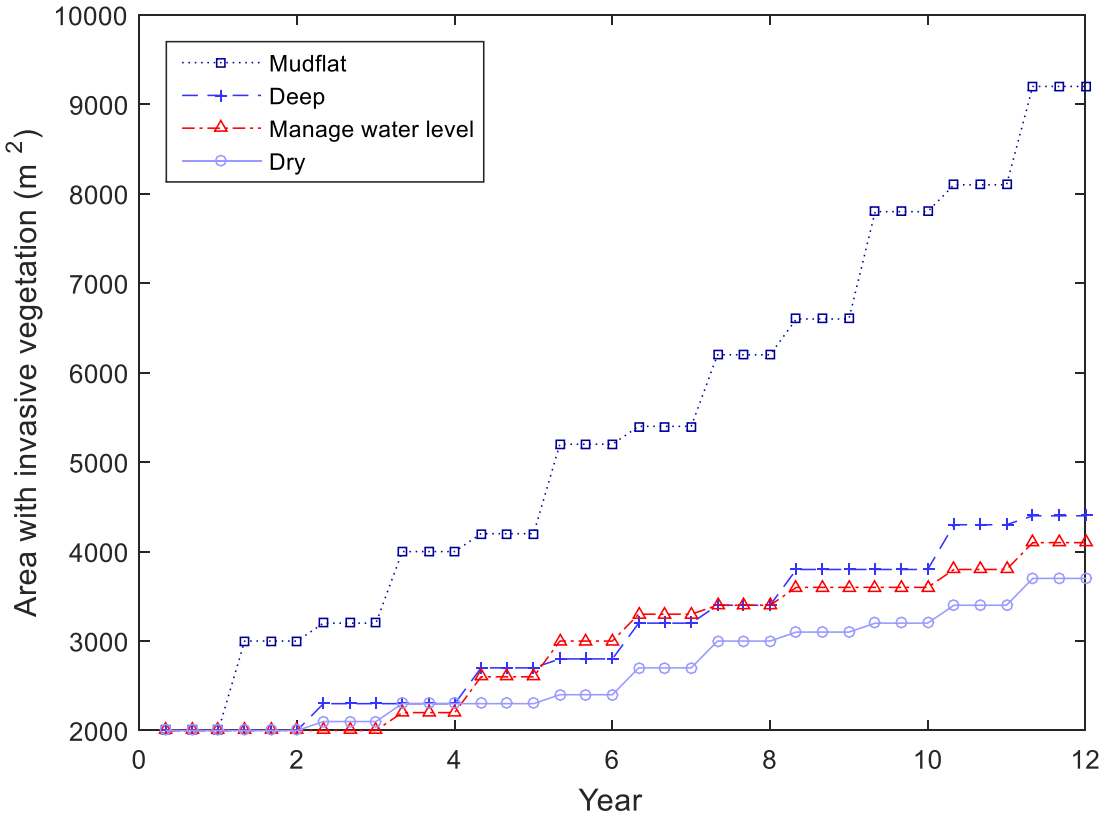

Figure 4.9. Invasive vegetation growth over time under different hydrologic conditions

4.4.1.3. Using AMPS to Manage *Phragmites*

AMPS can simulate the *Phragmites* removal under different patch size conditions and simulation results can inform *Phragmites* control efforts. For example, we simulated the effects of vegetation control under two conditions (Figure 4.10): partially controlling larger patches and completely eradicating small patches. We started each simulation with 80 cells (8000 m^2) of invasive vegetation distributed in two patches (Figure 4.10A) and asssumed there were resources to eradicate (remove) invasive vegetation in eight cells (black cells, Figure 4.10A and C). Subsequent simulation results over 4 years show that partial control of the larger patch (Figure 4.10A) later leads to more cells with invasive vegetation (Figure 4.10B) than completely eradicating the smaller patch (Figure 4.10D).

Thus, managers should completely eradicate small patches rather than partially eradicate large patches because small patches quickly expand outward on all sides to spread to a larger adjacent area (Figure 4.10.B).

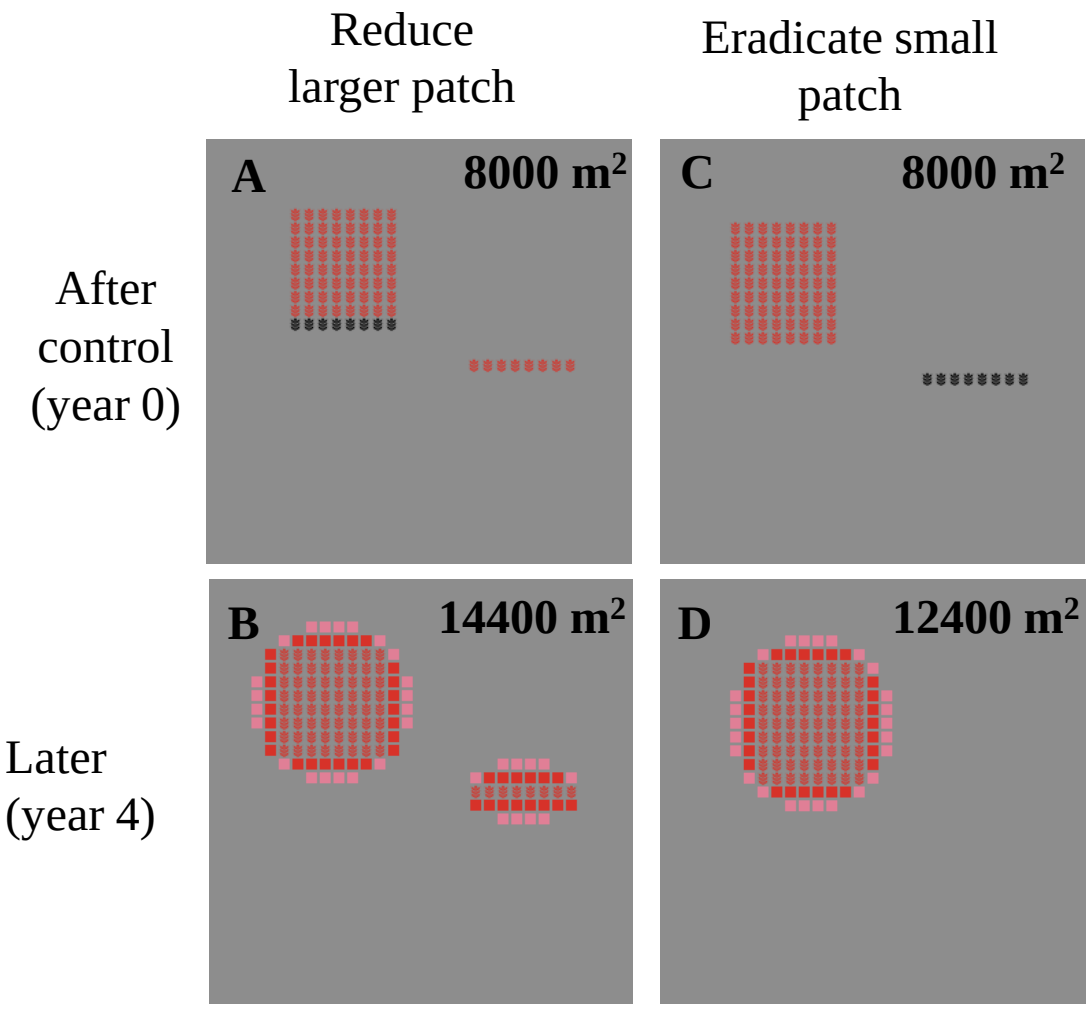

Figure 4.10. Simulated *Phragmites* spread under different management control shows that partial control of a larger patch (panel A) later gives rise to more *Phragmites* (panel B) than complete eratication of a small patch (panel D). Red cells (plant shape) represent the initial *Phragmites* cover, black cells represent the *Phragmites* removed by control efforts, red and pink squares represent the vegetation spread after 4 years, and numbers in the upper right corner represent the total area with *Phragmites*.

4.4.2. SWAMPS-Dynamic Vegetation to Improve Wetland Management

We selected and ran five scenarios to show the advantages of SWAMPS-Dynamic Vegetation response over SWAMPS Linear Vegetation response, and evaluate the impact – independently and simultaneously – of allocating water and removing vegetation on wetland performance at the Refuge.

Scenario 1 presents the SWAMPS-Linear Vegetation response, where the model recommends water allocation and invasive vegetation removal to improve wetland habitat performance (*WU*). This scenario does not consider the dynamic interaction between invasive vegetation and water level. Scenario 2 incorporates the dynamic vegetation response to hydrologic conditions and we assume mature invasive vegetation (i.e., rhizomes/seeds state) as initial conditions of the optimization. Scenario 2 identifies water levels that minimize the effects of invasive vegetation spreading and satisfy water habitat requirements simultaneously in wetlands. Comparing scenarios 1 and 2 (Table 4.3) shows that SWAMPS-Dynamic Vegetation (Base Case) improves the wetland performance metrics (*WU*) by more than 9 km^2/year of wetland habitat (in comparison to the prior model, SWAMPS-Linear Vegetation). This result is because SWAMPS-Dynamic Vegetation recommends water levels (deep and dry conditions) in wetland units that limit the spreading of invasive vegetation, which results in better wetland performance than SWAMPS-Linear Vegetation.

In scenario 3, we identified the impact of removing invasive vegetation on wetland performance using SWAMPS-Dynamic Vegetation. This scenario is produced by allowing the model to recommend vegetation removal but simulating wetland unit water depths measured in 2008 at the Refuge. Scenario 3 shows that removing invasive

vegetation and using the static water levels observed in wetland units in 2008 reduces wetland habitat performance by 318 km^2/year with respect to the base case. This result shows the importance to remove invasive vegetation and dynamically managing water level in wetland units to control invasive vegetation spread and better satisfy water requirements at the Refuge.

Table 4.3. Weighted Usable Area for Wetlands Obtained Through the Application of SWAMPS Under Different Vegetation Response, Water Allocation, and Vegetation Removal Actions at the Refuge

	Scenario	Vegetation response	Model recommends water allocation	Model recommends vegetation removal	Spending on vegetation removal ($1000/year)	Weighted usable area for wetlands WU (Km^2/year)
1	Prior	Linear	Yes	Yes	180	424
2	Base case	Dynamic	Yes	Yes	180	433
3	Removing vegetation	Dynamic	No[a]	Yes	180	115
4	Recommending water allocation	Dynamic	Yes	No removal	0	399
5	No action	Dynamic	No[a]	No removal	0	83

[a] Simulated water depth measured in 2008 at the Refuge

In scenario 4, we evaluate how the model performs under no removal of invasive vegetation but allowing the model to recommend water allocations. Results show that wetland habitat performance at the Refuge is reduced by almost 35 km^2/year with respect to the base case. Here, no expenses for vegetation removal were incurred. This finding highlights the advantage of SWAMPS-Dynamic Vegetation to allocate water to minimize invasive vegetation spread, save financial resources and provide wetland habitat

simultaneously. Managers at the Refuge should allocate water seeking deep (during winter and early spring) and dry conditions (during summer months) to minimize the effects of invasive vegetation spread and improve the wetland habitat performance.

Finally, in scenario 5, we evaluate SWAMPS-Dynamic performance absent water management and vegetation removal. This scenario shows that wetland habitat performance is reduced by 350 km^2/year (the lowest performance of any scenario). These results are because both static water level (e.g., mudflat condition) and no removal of invasive vegetation allow invasive vegetation to spread, limit water-bird requirements, and consequently reduce wetland performance.

4.5. Discussion

4.5.1. The Importance of Remote Sensing Images During AMPS Simulation

We use Landsat images of the Refuge between 2007 and 2011 to estimate initial vegetation cover, calibrate and validate model simulation results. We found that the classified Landsat imagery and AMPS simulation model agreed on invasive vegetation cover in 59.4% and 67.2% of the pixels in wetland units used, respectively, for the model calibration and validation. Also, we found that the difference in vegetation response using AMPS simulation and Landsat images were 91.0% and 97.9% for the calibration and validation respectively. These results highlight a tradeoff between precision and the difference in vegetation response (Figure 4.4). In addition, model performance can be affected by different factors, such as: (1) quality of spatial data (e.g., low resolution of remote sensing images reduces the precision to detect invasive vegetation), (2) invasive vegetation area and time of simulation (i.e., bigger areas or more time in the simulation

can involve lower precision), (3) cell size in the AMPS simulation (e.g., a small cell size can improve the spatial spreading arrangement of invasive plants, but it can increase the computational time), and (4) hydrological conditions in wetland units, which can affect the invasive vegetation detection (e.g., deep water levels in wetland units can submerge invasive vegetation and limit its detection using satellite images).

Even though Landsat images have low resolution (30 m), their 16-day temporal availability over four decades and free availability make Landsat imagery convenient for monitoring vegetation cover and flooded areas in wetlands. The application of remote sensing data in AMPS simulation provides a useful way to: (1) identify invasive vegetation in wetlands that can be input in AMPS as initial invasive vegetation condition and can help to predict what wetlands areas are most likely to be infested with invasive vegetation, (2) perform the calibration of threshold parameter in the AMPS model, and (3) test the accuracy of model results through the comparison of agreement of pixel with invasive vegetation in the AMPS simulation and remote sensing data.

4.5.2. The AMPS Tool

AMPS allows us to quantify invasive vegetation response to changes in three hydrologic conditions (dry, mudflat, deep) and four plant life stages (seeds, seedling/ramet, rhizomes and rhizome/seed stages). The model can be used to simulate the effects of vegetation removal under a different patch size conditions. For example in Figure 4.10, the model suggests to completely eradicate small patches rather than partially control larger patches to increase the effectiveness of invasive vegetation control.

AMPS simulation also shows how vegetation spreading is proportional to the size of existing stands of invasive vegetation (Figure 4.10 B). This result reflects that large patches have more contact area with their neighborhood and, consequently, more likelihood that neighbhor areas would be infested with invasive vegetation. However, partial control of large patches makes controled areas more vulnerable to invasion and remaining infested cells continue to spread by rhizomes/stolons and seeds reproduction. Thus, managers should completely eradicate small patches rather than eradicate part of large patches and detect invasive vegetation early and respond rapidly. Although this recommendation is described in previous management plans and research [e.g., *NISC*, 2003; *Buhle et al.*, 2011], our work is the first modeling tool to quantify invasive *Phragmites* spread considering changes in space, time, hydrologic condition and over different plant life stages. AMPS allows users to simulate different scenarios (e.g., change patch size or shape) to quantify the infested areas and identify different management strategies to reduce invasive vegetation spread.

The AMPS also shows that water depth manipulation during the life stages of *Phragmites* can be used to minimize the impact of its spread (Figure 4.9, red line). For example, during the seedling stage, managers should seek deep water conditions and avoid mudflat conditions. Deep conditions increase the accumulation of toxics in the roots and prevent plant respiration of *Phragmites* in the seedling stage [*Mauchamp et al.*, 2001]. In addition, it is important to avoid mudflat conditions that enhance rhizomes penetration into the substrate and improve anchorage of invasive plant [*Weisner and Strand*, 1996]. AMPS also shows that dry conditions can minimize the effects of vegetation spreading (Figure 4.9). However, recommending longer periods of dry

condition in wetlands is not realistic because desireable wetland plants also require water. Maintaining deep conditions over long time periods to reduce *Phragmites* spread can also be unrealistic because wetland managers are limited by the water available to supply their wetlands. Therefore, the SWAMPS – Dynamic Vegetation fills an important niche for managers by suggesting how managers can allocate water among wetlands and remove invasive vegetation to improve wetland performance while considering water availability, network conveyance, canal capacities, existing vegetation cover, and vegetation interaction with water.

4.5.3. Importance of SWAMPS-Dynamic Vegetation Response

SWAMPS-Dynamic Vegetation allows model users to (1) identify how invasive vegetation responds to the dynamic effects of water levels and (2) recommend water levels to minimize the invasive vegetation spread and improve wetland habitat performance simultaneously. Implementation of this tool at the Refuge suggests that invasive vegetation control and water allocation can synergistically minimize invasive vegetation spread and improve the wetland habitat performance. This finding is implemented in the base case scenario (Table 4.3), where the model recommends invasive vegetation control and water allocation based on both: (1) invasive vegetation response to dry, mudflat and deep water conditions and (2) water requirement of priority bird species. Base case scenario shows the highest wetland performance in comparison to any other scenarios. This result suggests that manipulating water levels and timing of flows (seek deep water condition in winter and early spring and dry conditions during summer months) allows managers to increase the wetland suitable area to 350 km^2/year (in comparison to no management actions). Thus, the Refuge will be benefited from

additional 350 km^2/year of suitable hydrological and ecological conditions for priority bird species.

Also, this tool shows that wetland managers can provide suitable wetland habitat, even though invasive vegetation removal is not implemented. Scenario 4 (Table 4.3) shows that managers can save $180,000 per year and still provide suitable wetland habitat in 399 km^2/year. This finding highlights the importance of dynamic water depth allocation to control invasive vegetation and improve wetland habitat performance.

4.5.4. Implications for the Refuge

AMPS shows *Phragmites* spreads less when managers control the plant in the seed or seedling stages and in small patches with complete eradication, rather than partial control of larger patches. This finding contrasts with current control practices at the Refuge where managers only begin control efforts after *Phragmites* covers 10% of total area in a wetland unit [*Olson*, 2007]. Rather Refuge managers should eradicate small patches completely and immediately, not delay removal until invasive vegetation covers 10% of a wetland unit.

AMPS results support efforts to manipulate water levels in wetland units according to life stages of *Phragmites* to reduce invasive vegetation growth. However, currently wetland managers at the Refuge neither manipulate water levels to control invasive vegetation in wetland units, nor monitor the life stages of *Phragmites*, this is because they have limited staff to manually open and close gates in each wetland unit and also, there is not a permanent monitoring of invasive vegetation and plant life stages. Therefore, managers should allocate sufficient financial and personnel resources to operate wetland unit gates or install an automatic system to control gates that allow them

to change water levels according to life plant stages. Also, they should monitor invasive vegetation more frequently using field survey and remote sensing images.

Refuge managers participated in the model development and they are excited by the key findings and recommendations. They are eager to further apply the modeling tools in their future management work. Further work is needed to implement a graphical user interface for the SWAMPS-Dynamic Vegetation that allows them to more quickly enter and modify model inputs, view model results, and identify appropriate water and vegetation management strategies.

4.6. Conclusions

We develop a set of tools to simulate the spread and control of invasive *Phragmites* which managers can use to improve wetland performance in an arid landscape with limited water resources and management budget. We apply an agent-based approach to quantify invasive *Phragmites* spread as a function of ecologically-relevant hydrologic conditions (dry, mudflat, deep) and plant life stage (i.e., seeds, seedling/ramet, rhizomes, rhizome/seed states). The agent-based model is comprised by agents that represent the invasive plants and their four progressive life stages of plant growth. Agent states change in time and space according to the interaction with each other and with their hydrological conditions. This interaction is represented by a set of rules that specify whether *Phragmites* plants are present in the current cell given the agent state in the previous time-step, hydrologic condition, and agents present in the neighboring cells. We repeat the rules' evaluation in each time-step to simulate *Phragmites* spread.

We use remote sensing Landsat images, supervised classification, and parallel coordinates to calibrate and validate the model in diked wetlands at the Bear River Migratory Bird Refuge (Utah) between 2007 and 2011. Comparison of Landsat images and the simulation model shows a precision of 59.4% and 67.2% for the calibration and validation respectively, as well as a difference in vegetation response of 91.0% and 97.9%. Results of the model simulation quantify *Phragmites* spread under different hydrological conditions. Analysis of water conditions and patch sizes suggests that: (1) manipulating water levels at the appropriate time and *Phragmites* life stage can reduce invasive vegetation spread, and (2) Refuge managers can better prevent spread by completely eradicating small patches rather than partially controlling larger patches or delaying removal until invasive vegetation covers 10% of the wetland unit.

Results of the agent-based model were embedded into an existing optimization model to dynamically estimate invasive plant spread as a function of water level changes and plant life stages. This embedding combines the hydrologic conditions and spread rate of invasive vegetation to cross temporal and spatial scales and transfer data from an agent-based simulation model to an optimization model. As a result, the improved optimization model suggests invasive vegetation control and water management actions to improve wetland performance that consider dynamic vegetation growth in response to hydrology, network conveyance and a limited budget to control invasive vegetation. Application of the improved optimization model shows that the Refuge will be benefited from additional 350 Km^2 of suitable habitat for priority bird species from the dynamic water management and vegetation control in wetlands.

Overall, this chapter develops and demonstrates an agent-based modeling approach to quantify the spread of *Phragmites* and a novel method that embeds the agent-based results into an optimization model. This model recommends management strategies to identify efficient ways to allocate scarce resources, manage invasive vegetation and improve wetland performance.

Appendix 4.1. Formulation of System Optimization Model in Wetlands to Allocate Water and Manage Plant Spread (SWAMPS - Dynamic Vegetation)

This appendix presents the mathematical formulation of the SWAMPS–Dynamic Vegetation model. This model recommends water allocation and vegetation control actions to improve wetland habitat performance and extends a prior wetland optimization model (see Chapter 3) to include a dynamic response function and relationship between wetland water levels and invasive vegetation growth. This relationship is parameterized using results from an agent-based model of vegetation spread. The extension substitutes Equations 4.1, 4.2, 4.3 and 4.4 as new constraints that describe invasive vegetation spread through time. The main components of the SWAMPS-Dynamic Vegetation model are:

Indices:

- Time (t) [month]
- Wetland unit (w)
- Priority bird species (s)
- Location nodes in the conveyance network (i,j)

Decision Variables:

- Water depth (wd) [units in m] which is a function of the Storage (S) [ha-m].

- Invasive vegetation removal (*RV*) [quantified as the percentage of removed invasive vegetation area within a wetland unit divided by the total area of the wetland unit].

Objective Function: The objective function (Eq. 4.5) maximizes the sum of the weighted usable area for wetlands (*WU*) across time and wetland locations and allows us to quantify wetland performance in units of area (m^2). *WU* is the product of two expressions: the first expression shown in square brackets combines specific habitat suitability indices for water depth (*HW*) and invasive vegetation cover (*HV*), and uses the weighting parameter, $sw_{t,s}$ (unitless), to prioritize among bird species *s*, in a particular time *t*. The habitat suitability index (unitless) represents the capacity of a given habitat attribute (such as water depth or vegetation cover) to support selected bird species. Habitat suitability ranges from 0 (poor) to 1 (excellent) habitat quality. For example, wetland units highly infested with *Phragmites* will have lower value (close to 0) of habitat suitability related to invasive vegetation (*HV*). This lower value is because higher infested area with *Phragmites* represents an undesirable habitat conditions for bird species and therefore lower wetland habitat performance.

The second expression, $a_{t,w}(S_{t,w})$, is the flooded area $a_{t,w}$, which is itself a function of storage ($S_{t,w}$) in a particular time *t* and wetland unit *w* and serves as an additional weight on composite habitat suitability. Together, the objective function maximizes the surface area available with suitable condition for priority species.

$$Maximize WU = \sum_{t,w}\left[\left(\frac{\sum_{s} sw_{t,s}\cdot HW_{t,w,s}\cdot HV_{t,w,s}}{\sum_{s} sw_{t,s}}\right)\cdot a_{t,w}\left(S_{t,w}\right)\right] \quad (4.5)$$

Equation 4.5 is subject to the following constraints:

i. **Mass balance on the Refuge System Network**

Water allocation is limited by water availability, conveyance losses, evaporation, and water mass balance at each time *t* and node *i*.

$$in_{t,i} + \sum_j lq_{j,i} \cdot Q_{t,j,i} - \sum_j Q_{t,i,j} - le_t \cdot a_{t,i}(S_{t,i}) = S_{t,i} - S_{t-1,i} \quad , \quad \forall t, i \tag{4.6}$$

where $in_{t,i}$ (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*; $Q_{t,i,j}$ (ha-m/month) is the flow rate during time *t* conveyed from node *i* to another node *j*; le_t (m) is the evaporation during time period *t*; $S_{t-1,i}$ (ha-m) is the storage in the previous time-step.

ii. Limited Conveyance and Storage Capacity in Wetlands

$$qm_{ij} \le Q_{t,i,j} \le qx_{ij} \quad , \quad \forall t, i, j \tag{4.7}$$

$$sm_i \le S_{t,i} \le sx_i \quad , \quad \forall t, i \tag{4.8}$$

where $qm_{i,j}$ 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; sm_i and sx_i (each ha-m) are, respectively, the minimum and maximum water storage capacity at node *i*; and *Q* and *S* are as defined previously.

iii. Dynamic Water-Invasive Vegetation Interaction

Dynamic interaction between water levels and invasive vegetation growth are parameterized using results of an agent-based model to simulate *Phragmites* spread (AMPS). To embed AMPS results to SWAMPS-Dynamic Vegetation, first, we convert from discrete water depth to continue water depth (Eq. 4.1); second, we calculate the spread rate of invasive vegetation spread for each water depth category *h* (dry, mudflat and deep) (Eq. 4.2). Third, we estimate the invasive vegetation response to continuous water level changes (Eq.4.3). Vegetation response is calculated for each wetland unit, and for each month (Eq. 4.4).

$$hydrologic\ classification_{t,i,h} = fa_h\left[wd_i\left(S_{t,i}\right)\right] \ , \quad \forall t,i,h \tag{4.1}$$

$$spread\ rate_{t,h} = \left(\frac{area_{t,h} - area_{t-1,h}}{area_{t-1,h}}\right) \ , \quad \forall t,h \tag{4.2}$$

$$VR_{t,i} = \frac{ta_i \cdot IV_{t-1,i} \cdot \sum_h \left(\left(hydrologic\ classification_{t,i,h}\right) \cdot \left(spread\ rate_{t,h}\right)\right)}{\sum_h \left(hydrologic\ classification_{t,i,h}\right)}, \quad \forall t,i \tag{4.3}$$

$$IV_{t,i} = IV_{t-1,i} + \left[\frac{IV_{t-1,i} \cdot \sum_h \left(\left(hydrologic\ classification_{t,i,h}\right) \cdot \left(spread\ rate_{t,h}\right)\right)}{\sum_h \left(hydrologic\ classification_{t,i,h}\right)}\right] - RV_{t,i}, \quad \forall t,i \tag{4.4}$$

where the hydrologic classification (unitless) is used to convert from discrete water depth to continuous water depths and it is in a function $(fa)_h$ of water depth (wd_i) which is itself a function of storage ($S_{t,i}$) of a wetland unit. Spread rate (m^2/m^2 month) quantify how much invasive vegetation cover (*area*) spread with respect of invasive vegetation cover in

previous time *t;* $VR_{t,i}$ (m^2) is the invasive vegetation growth during time period *t* in wetland unit *i*, $IV_{t-1,i}$ is the invasive vegetation cover in the wetland unit in time period *t* in wetland unit *i*, ta_i is the total area in wetland unit *i* and $RV_{t,i}$ is the invasive vegetation that managers remove in a wetland unit *i* in time *t*.

iv. Limited Financial Budget to Reduce Invasive Vegetation

$$\sum_{t,w} RV_{t,w} \cdot ta_w \cdot uc_t \leq b \tag{4.9}$$

where ta_w (m^2) is the total area of the wetland unit *w*, uc_t ($/$m^2$) is the unit cost to remove invasive vegetation during time period *t*, *b* ($) is the available financial budget to remove invasive vegetation, and $RV_{t,w}$ is the removal percentage defined previously.

A final set of constraints require the decision variables *S, Q, WD, IV, VR* and *RV* to be non-negative. Equation (4.5) subject to constraints (4.1) to (4.4) and (4.6) to (4.9) comprise a non-linear optimization program that identify water levels that minimize the effects of invasive vegetation spreading and satisfy water habitat requirements simultaneously in wetlands.

References

Ailstock, M. S., C. M. Norman, and J. P. Bushmann (2001), Common Reed Phragmites australis: Control and effects upon biodiversity in freshwater nontidal wetlands, Restoration Ecol., 9(1), 49-59.

Asaeda, T., and S. Karunaratne (2000), Dynamic modeling of the growth of Phragmites australis: Model description, *Aquat. Bot.*, *67*(4), 301-318.

Avers, B., R. Fahlsing, E. Kafcas, J. Schafer, T. Collin, L. Esman, E. Finnell, and A. Lounds (2009), *A Guide to Control and Management of Invasive Phragmites*, Second ed., U.S. Fish and Wildlife Service, Washington, D.C.

Bennett, D. A., and W. Tang (2006), Modelling adaptive, spatially aware, and mobile agents: Elk migration in Yellowstone, *Intl. J. Geographical Information Sci.*, *20*(9), 1039-1066.

Bernthal, T. W., and K. G. Willis (2004), Using Landsat 7 Imagery to Map Invasive Reed Canary Grass., U.S. Environmental Protection Agency, Washington, D.C.

Buhle, E. R., B. E. Feist, and R. Hilborn (2011), Population dynamics and control of invasive Spartina alterniflora: Inference and forecasting under uncertainty, *Ecol. Appl.*, *22*(3), 880-893.

Bussieck, M. R., and A. Meeraus (2004), General algebraic modeling system (GAMS), *Appl. Optimization*, *88*, 137-158.

Chambers, R. M., L. A. Meyerson, and K. Saltonstall (1999), Expansion of Phragmites australis into tidal wetlands of North America, *Aquat. Bot.*, *64*(3–4), 261-273.

Chambers, R. M., D. T. Osgood, D. J. Bart, and F. Montalto (2003), *Phragmites australis* invasion and expansion in tidal wetlands: Interactions among salinity, sulfide, and hydrology, *Estuaries*, *26*(2), 398-406.

Coops, H., and G. Van Der Velde (1995), Seed dispersal, germination and seedling growth of six helophyte species in relation to water-level zonation, *Freshwat. Biol.*, *34*(1), 13-20.

Coops, H., J. T. Vulink, and E. H. Van Nes (2004), Managed water levels and the expansion of emergent vegetation along a lakeshore, *Limnologica-Ecol. and Manage. Inland Waters*, *34*(1-2), 57-64.

Davis, C., and I. Nikolic (2010), Introduction to Agent Based Modeling, TU Delft University of Technology. (Available at http://collegerama.tudelft.nl/Mediasite/ Play/3f0a8278a4844548a35372eb4ff695371d)

Ekstam, B., R. Johannesson, and P. Milberg (1999), The effect of light and number of diurnal temperature fluctuations on germination of Phragmites australis, *Seed Sci. Res.*, *9*(02), 165-170.

Fennell, M., J. E. Murphy, C. Armstrong, T. Gallagher, and B. Osborne (2012), Plant Spread Simulator: A model for simulating large-scale directed dispersal processes across heterogeneous environments, *Ecol. Model.*, *230*(0), 1-10.

Grimm, V., and S. F. Railsback (2005), *Individual-based Modeling and Ecology*, Princeton University Press, New Jersey.

Gucker, C. L. (2008), Phragmites australis. In: Fire Effects Information System, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. (Available at http://www.fs.fed.us/database/feis/ plants/graminoid/ phraus/all.html)

Hastie, T., R. Tibshirani, J. Friedman, T. Hastie, J. Friedman, and R. Tibshirani (2009), *The Elements of Statistical Learning: Data mining, inference, and prediction.*, Second ed., Springer, New York.

He, H. S., and D. J. Mladenoff (1999), The effects of seed dispersal on the simulation of long-term forest landscape change, *Ecosystems*, *2*(4), 308-319.

Hudon, C., P. Gagnon, and M. Jean (2005), Hydrological factors controlling the spread of common reed (Phragmites australis) in the St. Lawrence River (Québec, Canada), *Ecoscience*, *12*(3), 347-357.

Huth, A., and C. Wissel (1994), The simulation of fish schools in comparison with experimental data, *Ecol. Model.*, *75–76*(0), 135-146.

Inselberg, A. (2009), *Parallel coordinates Visual Multidimensional Geometry and Its Applications*, Springer, New York.

Johnston, R. M., and M. M. Barson (1993), Remote sensing of Australian wetlands: An evaluation of Landsat TM data for inventory and classification, *Marine and Freshwater Research*, *44*(2), 235-252.

Kettenring, K. M., and K. E. Mock (2009), Spread and Genetic Relatedness of Native vs. Introduced *Phragmites australis* in Utah Wetlands., Utah State University, Logan.

Kettenring, K. M., M. K. McCormick, H. M. Baron, and D. F. Whigham (2011), Mechanisms of *Phragmites australis* invasion: Feedbacks among genetic diversity, nutrients, and sexual reproduction, *J. Appl. Ecol.*, *48*(5), 1305-1313.

Kettenring, K. M., D. F. Whigham, E. L. G. Hazelton, S. K. Gallagher, and H. M. Weiner (2015), Biotic resistance, disturbance, and mode of colonization impact the invasion of a widespread, introduced wetland grass, *Ecol. Appl.*, *25*(2), 466-480.

Long, L. (2012), Predicting Invasion and Prioritizing Control of Phragmites Australis in Great Salt Lake Wetlands, in *Spring Runoff Conference*, edited by Utah State University, Logan.

Mack, R. N., D. Simberloff, W. Mark Lonsdale, H. Evans, M. Clout, and F. A. Bazzaz (2000), Biotic invasions: Causes, epidemiology, global consequences, and control, *Ecol. Appl.*, *10*(3), 689-710.

Marks, M., B. Lapin, and J. Randall (1994), Phragmites australis (P. communis): threats, management and monitoring, *Nat. Areas J.*, *14*(4), 285-294.

Mauchamp, A., S. Blanch, and P. Grillas (2001), Effects of submergence on the growth of Phragmites australis seedlings, *Aquat. Bot.*, *69*(2–4), 147-164.

McCarl, B., A. Meeraus, P. V. Eijk, M. Bussieck, S. Dirkse, and P. Steacy (2008), *GAMS User Guide*, edited by GAMS Development Corporation, Washington, D.C.

Meyer, K. I., and B. Li (2013), A spatial model of plants with an age-structured seed bank and juvenile stage, *SIAM J. Appl. Math.*, *73*(4), 1676-1702.

NISC (2003), General Guidelines for the Establishment and Evaluation of Invasive Species Early Detection and Rapid Response Systems. Version 1, edited by National Invasive Species Council, Washington, D.C.

Norris, L., J. E. Perry, and K. J. Havens (2002), A Summary of Methods for Controlling *Phragmites* australis., Virginia Institute of Marine Science, Virginia.

Olson, B. E. (2007), *Phragmites Control Plan, Bear River Migratory Bird Refuge.*, U.S. Fish and Wildlife Service, Brigham City, Utah.

Pimentel, D., R. Zuniga, and D. Morrison (2005), Update on the environmental and economic costs associated with alien-invasive species in the United States, *Ecol. Econ.*, *52*(3), 273-288.

Railsback, S. F., and V. Grimm (2011), *Agent-based and Individual-based Modeling: A Practical Introduction*, Princeton University Press, New Jersey.

Rickey, M. A., and R. C. Anderson (2004), Effects of nitrogen addition on the invasive grass *Phragmites* australis and a native competitor Spartina pectinata, *J. Appl. Ecol.*, *41*(5), 888-896.

Saltonstall, K. (2002), Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America, *Proc. National Academy of Sciences*, *99*(4), 2445.

Smith, L., N. Euliss, D. Wilcox, and M. Brinson (2008), Application of a geomorphic and temporal perspective to wetland management in North America, *Wetlands*, *28*(3), 563-577.

Stoll, P., and J. Weiner (2000), *A Neighborhood View of Interactions among Individual Plants. The Geometry of Ecological Interactions: Simplifying Spatial Complexity*, Cambridge University Press, Cambridge.

Tisue, S., and U. Wilensky (2004), *NetLogo: A Simple Environment for Modeling Complexity*, paper presented at International Conference on Complex Systems, Boston.

Van Wilgen, B., D. Richardson, and S. Higgins (2000), Integrated Control of Invasive Alien Plants in Terrestrial Ecosystems, paper presented at Best Management Practices for Preventing and Controlling Invasive Alien Species, CapeTown.

Vanderlinder, M. S., C. M. U. Neale, D. E. Rosenberg, and K. M. Kettenring (2014), Use of remote sensing to assess changes in wetland plant communities over an 18-year period: A case study from the Bear River Migratory Bird Refuge, Great Salt Lake, Utah, *West. N. Am. Nat.*, *74*(1), 33-46.

Weisner, S. E. B., and J. A. Strand (1996), Rhizome architecture in *Phragmites australis* in relation to water depth: Implications for within-plant oxygen transport distances, *Folia Geobot. Phytotaxon., 31*(1), 91-97.

Zedler, J. B., and S. Kercher (2004), Causes and consequences of invasive plants in wetlands: Opportunities, opportunists, and outcomes, *Crit. Rev. Plant Sci., 23*(5), 431-452.

CHAPTER 5

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

5.1. Summary and Conclusion

In this dissertation, a series of tools and approaches are developed to: (1) select a combination of best management practices (BMPs) to reach water quality standards, (2) recommend water allocation and management of invasive vegetation to improve wetland bird habitat, and (3) quantify invasive vegetation spread in wetlands, spatially and temporally, and use that information to recommend strategies to control the spread of invasive *Phragmites*. These tools are presented in three independent studies in Chapters 2, 3 and 4.

In Chapter 2, we address the problem of excess phosphorus loading in the Echo Reservoir watershed in Utah. We develop a simple linear optimization model that selects the cost-effective combination of BMPs to reduce non-point sources of phosphorus loading within three sub-watersheds (Chalk Creek, Weber River Below Wanship and Weber River Above Wanship). The model minimizes the cost of implementation of BMPs to meet phosphorus quality standard at the Echo Reservoir. The model is based on the Total Maximum Daily Load (TMDL) document which determines the water quality standard to reach. The model (1) tests the implementation feasibility of a load reallocation of the TMDL, (2) recommends how much area of BMP managers need to implement, and (3) identifies the number of sites required in a sub-watershed to meet a load reduction target. Model results suggest that BMPs for private land grazing, diffuse runoff and land applied manure can feasibly reduce phosphorus loads in the three sub-watersheds to reach specific water quality standard at the Echo Reservoir. This tool was

developed to help regulators and watershed managers to reduce phosphorus load in watersheds.

In Chapter 3, we address the problem of water allocation and invasive vegetation in diked wetlands. A novel approach was developed and applied to recommend water allocations and invasive plant management to improve hydro-ecological performance of diked wetlands. First, we measure this performance using an intermediate and overall performance metrics. The intermediate metrics are habitat suitability indices that represent the capacity of a given habitat to support selected indicator species. We combine these indices with the wetland flooded area and species weights to create an overall metric defined as the weighted usable area for wetlands (*WU*). The *WU* represents the surface area available in the wetland that provides suitable hydrological and ecological conditions for selected indicator species. Second, we embed this hydro-ecological performance as an objective function in a systems optimization model. The model maximizes *WU* performance under hydrological, ecological, and management constraints to recommend water allocation and invasive vegetation control decisions.

The model was applied in the Bear River Migratory Bird Refuge, Utah. The model was run for a base case representing hydrologic conditions in 2008 and seven other scenarios that independently consider changes in wetland gates operation, water availability, financial budget, and vegetation responses. Systems model results show that there are opportunities to increase by three-fold the suitable habitat area in wetlands through increasing water level and more dynamically adjusting water levels in wetland units. Also the model shows that wetland habitat is more affected by limits on gate operations, water availability, and invasive vegetation responses rather than by the

financial budget to manage invasive vegetation. This modeling approach demonstrates a way to develop and apply hydro-ecological performance metrics in wetlands and embed those metrics in systems models to recommend management actions to improve wetland performance.

In Chapter 4, we address the problem of invasive *Phragmites* spread in wetlands. We developed a model to simulate invasive *Phragmites* spread in wetlands as a function of water level and plant life stages considering spatial and temporal factors. This model uses an agent-based approach and provides useful insights of the dynamics of *Phragmites* spread and control strategies. We use remote sensing Landsat images, supervised image classification, and parallel coordinates to calibrate and validate the model. Results of the agent-based model are embedded in the optimization model developed in Chapter 3 to obtain an improved optimization model that (i) calculates the dynamic invasive plant spread as a function of water level changes, and (ii) integrates water allocation, financial resources, and control of invasive vegetation. Results of this set of tools show that invasive vegetation control and water allocation can synergistically minimize invasive vegetation spread and improve the wetland habitat performance. Also, model suggests that the Refuge managers should completely erradicate small patches of *Phragmites* rather than partially eradicate large patches.

All models presented in this dissertation were developed with the participation of stakeholders and decision makers. State regulators from the Utah Department of Environmental Quality (model in Chapter 2) and wetland managers at the Bear River Migratory Bird Refuge (models in Chapter 3 and 4) have provided data and multiple rounds of feedback on the model and model's results.

Overall, this participatory modeling effort demonstrates (1) a simple approach to identify and select BMPs at a lower cost, (2) a novel approach to incorporate an ecological performance metric in a systems optimization model and recommend management actions to improve wetland bird habitat, (3) an approach to quantify the spread of *Phragmites*, and (4) a method that embeds agent-based results into an optimization model that recommends invasive vegetation control actions. Together, these tools provide informed decisions that identify efficient ways to allocate scarce resources to improve water quality and ecological performance of wetlands.

5.2. Management Recommendations

At the Echo Reservoir Watershed:

- Develop a specific plan to meet required reductions of the TMDL. This plan should consider a wider mix of BMPs. Cost, effectiveness, and area of BMPs implementation should help managers make informed decisions to allocate BMPs.
- Explore a more relaxed scenario of BMP's implementation, where phosphorus load reduction can be considered across sub-watersheds rather than specific load reduction in each sub-watershed.

At the Bear River Migratory Bird Refuge:

- Adjust water levels more dynamically in wetland units to improve hydro-ecological performance in wetlands. Wetland managers should install and use an automatic system to control gates or assign more personnel to adjust gates.
- Protect the Refuge's water right to prevent a drastic decline in wetland performance. Wetland performance declines rapidly for water availability close to

Refuge's annual water right (Figure 3.10). Refuge managers should be concerned about upstream water abstractions that reduce the water available to the Refuge and be very concerned if new abstractions infringe on the Refuge's water right.

- Use Landsat images to get preliminary information of vegetation cover and flooded areas in the wetlands. Even when Landsat images have low resolution (30 m), the temporal availability (16 days) and long continuous records can help managers to monitor vegetation cover and flooded areas in wetlands.
- Manage water levels according to the life stage of *Phragmites* to reduce invasive vegetation spread. Model's results in Chapter 4 show that changes in water level conditions can minimize invasive vegetation spread. However, these simulation results need to be validated in the field before its implementation. Controlled experiments of *Phragmites* spread with water level fluctuations are recommended to validate simulation findings.
- Eradicate small patches completely rather than partially controlling larger patches. Managers should allocate their resources to control invasive vegetation on specific wetland units with complete eradication rather than to partially control many wetland units.
- Detect invasive vegetation early and respond rapidly in contrast to the current control practices at the Refuge which wait to begin control efforts until *Phragmites* cover 10% of the total area in each wetland unit.

5.3. Future work

The system models presented in this dissertation identify opportunities to explore additional work to verify their benefits and extend their applicability. Future work includes:

- Determine where exactly a BMP should be located at the farm or field scale. The model in Chapter 2 identifies which BMPs should be implemented in a sub-watershed (not where to locate them within the sub-watershed). Remote sensing images, agent-based approach, and available field data will help to determine the implementation locations of BMPs on a larger scale.
- Extend the model in Chapter 3 to implement a more user-friendly interface. The system model was developed using different software (GAMS, MATLAB, HydroPlatform) and script languages that make it difficult to use for decision makers. Further work is needed to implement user interface that will allow managers to enter and modify model inputs, view model results, as well as develop their own scenarios.
- Extend the model in Chapter 3 to consider more hydrological and ecological variables that influence wetland performance. The current model considers water levels and invasive vegetation cover. Further system analysis should focus on including relevant variables such as nutrient levels and salinity.
- Extend the model in Chapter 3 to a multi-year analysis. The current tool considers a time period of one year. Further system analysis should focus on extending the time period analysis to multi-year. This extension will provide a better

understanding of how water allocation affects invasive *Phragmites* during its complete life period.

- Extend the model in Chapter 3 to explore effects of climate change in the Refuge. The Refuge's managers have shown their interest to use the model to explore the potential effects when snowpack melts earlier or in drought conditions. Available information (e.g., flow measures) will be required to accomplish this.
- Simulation of *Phragmites* spread (Chapter 4) shows that it is possible to reduce the *Phragmites* spread using water level variation during plant life stages. Further research in the field with controlled experiments of *Phragmites* spread and changes in water level is recommended to validate these simulation findings.
- Extend the model in Chapter 4 to simulate other plant invaders. A fundamental understanding of the biological characteristics of the invasive plant (e.g., life stages, mechanism of spread) and the interaction with hydrological conditions will be required to simulate other plant invaders.

APPENDIX

Permission Copyright Release

From: Omar Alminagorta [mailto:o.alminagorta@aggiemail.usu.edu]

Sent: Friday, June 06, 2014 1:24 PM

To: PERMISSIONS

Subject: Permission to reprint an article

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Omar Alminagorta

PhD Candidate

Civil and Environmental Engineering

Utah State University

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Subject: RE: Permission to reprint an article

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Dr. Bethany Neilson,

Our article, "Simple Optimization Method to Determine Best Management Practices to Reduce Phosphorus Loading in Echo Reservoir, Utah", in which you are a coauthor, reports an essential part of my dissertation. I would like your permission to reprint it as a chapter in my Thesis. I will include acknowledgments and appropriate citation of the article. Please advise me of any changes you require.

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Omar Alminagorta

I hereby give permission to Omar Alminagorta to reprint the following material in his dissertation.

"Simple Optimization Method to Determine Best Management Practices to Reduce Phosphorus Loading in Echo Reservoir, Utah." J. Water Resource. Plann. Manage., 139(1), 122–125.

Signed Bethany Neilson

Date 6/10/14

From: Omar Alminagorta

Sent: Friday, June 6, 2014 11:32 AM

To: berkeltes Tesfatsion

Dear Bereket,

Our article, "Simple Optimization Method to Determine Best Management Practices to Reduce Phosphorus Loading in Echo Reservoir, Utah", in which you are a coauthor, reports an essential part of my dissertation. I would like your permission to reprint it as a chapter in my Thesis. I will include acknowledgments and appropriate citation of the article as shown in the Journal of Water Resources Planning and Management.

Please indicate your approval of this request. This permission information will be included in a special appendix of my Thesis.

Thank you

Omar Alminagorta

Utah State University

From: <ber.kel.tes@aggiemail.usu.edu>

Date: Sat, Jun 7, 2014 at 11:01 AM

Subject: Re: Permission to Reprint Article

To: Omar Alminagorta <o.alminagorta@aggiemail.usu.edu>

Dear Omar,

It is an honor to have our article be part of your Ph.D. dissertation. Therefore, I gladly grant you my permission to reprint it as a chapter in your Thesis.

Thank you,

Bereket Tesfatsion

CURRICULUM VITAE

OMAR ALMINAGORTA
o.alminagorta@aggiemail.usu.edu

EDUCATION

PhD Candidate in Civil and Environmental Engineering – Water Resources Management, Utah State University (USU), May 2014

Master of Science in Irrigation Engineering, USU, May 2008

Bachelor of Science in Agricultural Engineering, National Agrarian University La Molina, Peru. Aug 2000

INTERESTS

System Modeling | Water Management | Remote Sensing

Optimization and Simulation for Environmental Purpose | Data Analysis

RESEARCH EXPERIENCE

Research Assistant, Civil & Environmental Engineering Department, USU

Aug. 2008 – May 2014

- Development of a system optimization model to improve environmental management.
    - Implement an approach to quantify wetland habitat performance
    - Develop a system model that recommends water allocations and vegetation control actions in wetlands. Model recommendations are subject to constraints such as water availability, spatial connectivity of

wetland, vegetation growth, plus financial and time resources available at Great Salt Lake wetlands. Presented at the AGU-Fall Meeting 2012

- Development of a model to identify the cost effective alternatives to reduce phosphorus loading at Echo Reservoir in Utah.

- Application of remote sensing to improve wetland management
  - Create a Matlab algorithm to process LandSat images and estimate flooded areas and invasive vegetation cover at the Great Salt Lake wetlands.
  - Application of remote sensing images to identify the hydrological-plant response relationships and mathematically represents them in a systems model.
- Development of model to simulate invasive vegetation in wetlands.
  - Develop, test, and calibrate and agent-based and cellular automata model approach to simulate invasive *Phragmites* spread.
  - Model application at the Bear River Migratory Bird Refuge, Utah.
- Integrated watershed Management.
  - Data mining analysis related to determine the relationship between drought and invasive vegetation in wetlands.
  - Testing Hydroplatform software to improve water allocation.
  - Application of parallel coordinates to analyze multivariate data.

Research Assistant, Irrigation Engineering Department, USU.

Sept 2006 – Aug 2008

- Assisted in the installation of water level recording system for flow measurement structures to enhance water delivery service in Cache Valley, Utah
- Worked in the installation of weather stations in Utah
- Assisted in the evaluation of sprinkler and surface irrigation in Panguitch, Utah
- Participated in the determination of the turgfrass water use using lysimeters, Utah Final Report

INVITED TALK/ CONFERENCES

Invited Lectures

- Management of Irrigation Systems class, USU. Feb.2014
- Water Resources Doctoral Program, National Agrarian University la Molina, Lima-Peru. Dec.2012
- Water Resource System Analysis class, USU. Sept. 2012
- Water Resources Engineering class, USU. Dec. 2011

Conferences Presentations

- EPA Region 8 Wetland Workshop, Utah, Sept. 2013
- Runoff Conference, USU, April 2013
- American Geophysical Union Fall Meeting, Dec. 2012
- Water Environment Association of Utah, April 2012
- World Environmental & Water Resources Congress, Rhode Island , May 2010

PROFESSIONAL EXPERIENCE

Technical Consultant, Ministry of Economy and Finances, Peru.

April 2003 – August 2006

- Evaluate multimillion dollar projects related to agriculture, education, water supply and others.
- Conducted training sessions for development and evaluation of projects.
- Participated in a team responsible for developing a methodology of natural hazards risk evaluation in governmental projects.
- Determined the financial feasibility of projects related to rehabilitate damages caused by natural disasters.

Engineer Assistant, Ministry of Agriculture, Peru, September 2001 – March 2003

- Design and supervision of river bank protection during the Plan for Prevention against Phenomenon "El Niño" 2002-2003, Lima-Peru.

INTERNSHIP EXPERIENCE

- Jequetepeque- Zaña Project (Peru), January to March 2001: Technical Evaluation of sediments of the Dam "Gallito Ciego".
- The Majes –Siguas Project (Peru), January to March 2000: Technical Evaluation of the hydraulic structures.

PUBLICATIONS

Published

- Rosenberg, D., **Alminagorta O.** (2012). Managing water for environmental and ecological purposes. *Published by Hydrology Section Newsletter, AGU.* hydrology.agu.org/pdf/AGUHydro-201207.pdf
- **Alminagorta,O**., Tesfatsion,B., Rosenberg,D., Neilson,B (2011) "Simple Optimization Method To Determine Best Management Practices To Reduce

Phosphorus Loading In Echo Reservoir, Utah" Jul 2011. *Journal of Water Resource Planning and Management-ASCE*. http://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29WR.1943-5452.0000224

- **Alminagorta,** O., D. E. Rosenberg, and K. M. Kettenring (2010), System Analysis to Improve Wetland Water Allocation at the Bear River Migratory Bird Refuge, Utah, paper presented at Proc.,World Environmental and Water Resources Congress, ASCE. http://ascelibrary.org/doi/abs/10.1061/41114(371)264.
- **Alminagorta O**., Merkley, G. (2009) "Transitional flow between orifice and non-orifice regimes at a rectangular sluice gate". *Published by Journal of Irrigation and Drainage Engineering, American Society of Civil Engineers*. Vol. 135, No. 3, pp. 382-387. http://cedb.asce.org/cgi/wwwdisplay.cgi?172542

Working Papers

- **Alminagorta, O**., D. E. Rosenberg, and K. M. Kettenring, Systems modeling to improve the hydro-ecological performance of diked wetlands, (Under Review).
- **Alminagorta, O**., D. E. Rosenberg, and K. M. Kettenring, Modeling invasive *Phragmites* spread to improve wetland management.

Theses

- "Systems optimization models to improve water management and environmental decision making", (2015). Department of Civil and Environmental Engineering, Utah State University, US.

  Advisor: Dr. David Rosenberg

- "Transitional flow between orifice and nonorifice regimes at a rectangular sluice gate", (2008). Department of Irrigation Engineering, Utah State University, US.
  Advisor: Dr. Gary Merkley
- "Uniformization of Flow for irrigation type INIA using microtubule emitter ", (2002). Department of Agricultural Engineering, National Agrarian University La Molina, Peru.
  Advisor: Angel Becerra Pajuelo

LANGUAGES

Spanish: Native

English: Speaking, Reading, Writing (Very Proficient)

Portuguese: Speaking, Reading (Basic)

COMPUTER SKILLS

MATLAB, GAMS, R, PYTHON, ARCGIS, HEC-RAS, Office, ERDAS, NetLogo.

AWARDS/HONORS

- 2012 American Society of Civil Engineers Northern Utah Branch, Scholarship
- 2008 Utah Water Research Laboratory, Graduate Research Assistantship
- 2007 Biological and Irrigation Engineering, Graduate Research Assistantship
- 2000 La Molina National Agrarian University, First Class Honors