

Rethinking Riverine Habitat Quality: Integrated Systems Modeling to Improve Watershed Habitat Management and Decision Making

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Abstract: River restoration and conservation projects use habitat quality indicators (e.g., Habitat Suitability Index) to monitor and quantify changes of one or a few habitat attributes (e.g. instream flow, bank stability, and flood regime). A more integrated approach representing broader watershed habitat components requires rethinking riverine habitat quality. Systems models provide decision makers with tools to quantify and understand interconnections between different habitat components. They help predict and account for potential changes in hydrologic, ecological, and management variables in water systems. Applying systems models in restoration practice requires developing and applying new and robust habitat quality indicators that capture dynamic hydrologic and ecological changes in a watershed system with minimal data-collection effort. We have developed a Watershed Habitat Performance (WHP) indicator, measured in unit area, which quantifies habitat suitability for watershed priority species. The WHP sums four sub-indicators representing the four main foci of restoration that vary spatially and temporally: aquatic life, riparian areas, floodplain zones, and impounded wetlands. The systems model maximizes watershed habitat performance by adjusting decision variables that effect the four sub-indicators. These variables include water depth, flow, re-vegetation, nonnative vegetation control, and control of river bank erosion. The optimization is subject to constraints such as water rights delivery requirements, infrastructure capacity, mass balance, and limited water availability and financial budget for management. We apply this integrated approach to the Lower Bear River, Utah to show how to better manage water to improve habitat quality, environmental watershed services, and support local efforts to secure water for wetlands and riparian areas. We demonstrate the WHP model along one segment of the river at two different time periods. Preliminary results show that the model captures different management actions which are reflected in the value of the WHP. Systems models can help make planning and monitoring river restoration more effective by allocating scarce resources to improve habitat quality.

Keywords: Restoration; Watershed Habitat; Systems Models; Optimization; Performance Indicators

1. INTRODUCTION

Ecological restoration and conservation projects aim to assist the recovery of a river system that has been degraded and damaged (SER 2004). River managers and restoration planners need dynamic and simple tools to help them improve river habitat and allocate scarce natural and financial resources. Habitat quality, however, is hard to quantify. In restoration science, existing habitat quality indicators such as the Habitat Suitability Index (HSI) (U.S. Fish and Wildlife Service 1981) describe a specific habitat attribute or a single species within the habitat or some hydrologic or ecologic changes within a specific time at a specific location. Use of these tools in practice is rare and limited (Wohl et al. 2005). It can also be misleading to use these indicators to communicate success (or failure) of restoration projects (Giller 2005; Palmer et al. 2005; Woolsey et al. 2007). This mismatch between science and practice requires introducing robust habitat quality indicators that can represent the entire watershed and its components. Embedding these indicators in a systems model of a watershed can further advance the practice of watershed restoration by identifying promising strategies and management actions to improve system (i.e. habitat) performance and quality. Systems models mathematically represent complex systems. They quantify the interconnections between system components such as between hydrologic and ecological variables and management decisions, and use one or more objective functions or performance indicators to quantify system performance. Managers can then maximize (or minimize) the value of the habitat performance indicator by adjusting one or multiple decision variables that they have control over. When the system performance objective represents habitat performance,

managers can use the systems model to identify promising management strategies to improve habitat quality.

We introduce a new set of quantifiable and measurable environmental and ecological performance indicators that riverine habitat improvement projects can embed in a systems model to help improve habitat quality at the watershed scale. We incorporate these indicators in a single-objective optimization model and apply the model to the Lower Bear River (LBR) watershed, Utah. This model supports existing restoration efforts (i.e. The Bear River Conservation Action Plan; CAP) by The Nature Conservancy and local authorities. The model helps managers and practitioners to rethink river restoration and redesign restoration planning and monitoring process to allocate scarce financial and water resources to improve habitat. The model encourages stakeholder participation by including stakeholders in the defining of performance indicators, selecting, and adjusting of model weights that vary spatially and temporally according to the priority species in addition to areas and seasons under concern. Section 2 introduces the optimization model while Section 3 presents the application to one river segment of the LBR at two time periods.

2. MODEL FORMULATION

The systems model is an optimization model with a single-objective function that maximizes the composite quality of the habitat under study by adjusting the values of some controlled hydrologic and ecologic variables. The systems model measures the values of four sub-indicators which collectively represent the performance indicator. Adjusting the values of the decision variables improve habitat quality within the system constraints. The model maximizes a composite habitat quality indicator that I refer to as Watershed Habitat Performance (WHP) which is measured in unit area (m^2). The WHP is composed of the weighted sum of four sub-indicators that include riparian areas, aquatic life, floodplain vegetation cover and impounded wetlands. These sub-indicators describe the key watershed components that river conservation projects try to protect and improve. Each sub-indicator quantifies the habitat suitability of its respective watershed component by selecting indicator species or habitat attributes that are of concern to managers. Habitat suitability quantifies either the condition (e.g. existence or abundance) of that indicator attribute (e.g. native vegetation) or the habitat ability to support indicator species (e.g. water depth required for cutthroat). The selected species and habitat attributes might change from one river to another. Therefore, the model is designed to be transferable by using suitability indexes that are based on literature or expert opinions. These indexes can be changed from one habitat to another to represent different priority species and habitat attributes.

Managers have control over ecological and hydrologic variables (i.e. decision variables; reservoir release, diversions, area to re-vegetate). Adjusting these variables control the watershed state variables (e.g. river water depth, native vegetation cover) which influence habitat suitability that is represented by the suitability indexes and the overall WHP (Figure 1). Any change (increase or decrease) in the decision variables (positive or negative) will affect watershed hydrology and ecology (e.g. water depth, native and nonnative vegetation cover). Those changes will be reflected in the values of the suitability indexes which represent the suitability of habitat to support living species. The suitability indexes take values between 0 (representing poor habitat conditions) and 1 (representing excellent habitat conditions). Each sub-indicator is quantified by multiplying a suitability index by an affected area. Finally, sub-indicators are aggregated together using weights that vary spatially and temporally to determine the overall WHP value which represents the entire habitat quality. The following sections outline how decision variables are incorporated in measuring and calculating the systems model objective function and sub-indicators.

2.1 Decision Variables

In regulated systems, river managers control several hydrologic variables such as reservoir releases, quantity of agricultural diversions and water inflow to wetlands. Managers also make ecological decisions like area to re-vegetate, nonnative vegetation area to control, and river bank length to protect from erosion. Managers can also build new infrastructure to store or divert water. The model formulation uses capital letters to indicate variables that represent these decisions and lower-case letters to describe model parameters.

2.2 Objective Function

The model objective is to maximize the WHP. This WHP is composed of the weighted sum of the four sub-indicators, representing the four watershed components as shown in eq. [1]. The model uses (t) for time (months), (i) for river segment between two nodes along the river, and (s) as an index representing the four sub-indicators (i.e. Ind_{rip} for riparian areas, Ind_{aq} for aquatic life, Ind_{nv} for floodplain vegetation nativity, and Ind_{wu} for Impounded wetlands). $w_{s,i,t}$ is the spatial and temporal weights for each sub-indicator and can take the value between 0 (not important) to 1 (important).

$$Max WHP = \sum_{s,i,t} w_{s,i,t} \times Ind_{s,i,t} \quad [1]$$

2.3 Sub-indicators

Each sub-indicator is calculated as a function of a group of decision and state variables by multiplying a suitability index by an affected area. Example habitat attributes are selected to demonstrate the calculation of each sub-indicator. Whereas multiple attributes are considered for any sub-indicator (e.g. different water depths for different fish species), we use a composite suitability index to represent habitat suitability for that habitat component (e.g. aquatic life).

2.3.1 Riparian Area Protection [RP]

Riparian areas include riverbanks adjacent to streams, which typically have high water table that interacts with plant roots. Protecting riparian areas entails primarily protecting river banks from eroding. The riparian protection sub-indicator, measured as area protected [RP (m^2)], quantifies the area at which river bank conservation practices (e.g. land easements, fencing) are implemented to minimize the sources of degradation and maintain healthy riparian zones. RP is calculated by multiplying a riparian suitability indicator [RI (unitless)] by the riparian surface area [A_r (m^2)] of each river segment as shown in eq. [2]. RI is an indicator that measures the suitability of the riparian area against the type (n) and length (L_n) of protection action implemented along the river stretch as shown in eq. [3]. RI value increases with the weighted effectiveness of protection measures implemented. Each protection action has a rating weight (rw_n) according to its effectiveness to protect the habitat. These weights are determined by expert opinions and can take values between 0, representing poor protection, to 1, representing excellent protection.

$$RP_{i,t} = RI_{i,t} \times A_{r,i,t}, \quad \forall i, t \quad [2]$$

$$RI_i = \frac{\sum_n rw_n \times L_n}{2 \times l_i}, \quad \forall i \quad [3]$$

2.3.2 Aquatic Life protection [AQ]

Aquatic species (e.g. fish, macroinvertebrates) are highly sensitive to the seasonal variations of water depth because it affects their spawning and metabolic rate (Munoz-Mas et al. 2012). Alteration of flow regime in rivers can lead to the extinction of native aquatic species or the introduction of nonnative ones with broader tolerance. The relationship between water depth and riverine HSI has been well-established in many literature based on the habitat suitability curves for different riverine species (e.g. Guay et al. 2000). If more than one priority species are studied, a Composite Suitability Index is calculated by multiplying the values of individual suitability indexes as shown in eq. [4]. Multiplication is based on Bovee (1986) assumption that environmental variables (e.g. water depth) have independent impacts on species and therefore the habitat's composite capacity to support species is calculated based on individual variables. Aquatic life suitability sub-indicator [AQ (m^2)] in location i and time t can be calculated by multiplying the habitat suitability index values for each priority species r [hsi_r (unitless; takes values of 0 to 1)], which are also functions of water flow [Q] by the channel surface area (A) according to eq. [5]. A (m^2) is a calculated by multiplying the channel length (l) by its width (W). Channel width is a function of flow [$w(Q)$] which managers can control through reservoir releases and diversions. The relationship between channel width and flow can be derived using Manning hydraulic equation (Finnegan et al. 2005), or using empirical data

$$AQ_{i,t} = \prod_{r=1}^R hsi_{i,r}(Q_{i,t}) \times A_{i,t}, \quad \forall i, t \quad [4]$$

$$A_{i,t} = w_i(Q_{i,t}) \times l_i, \quad \forall i, t \quad [5]$$

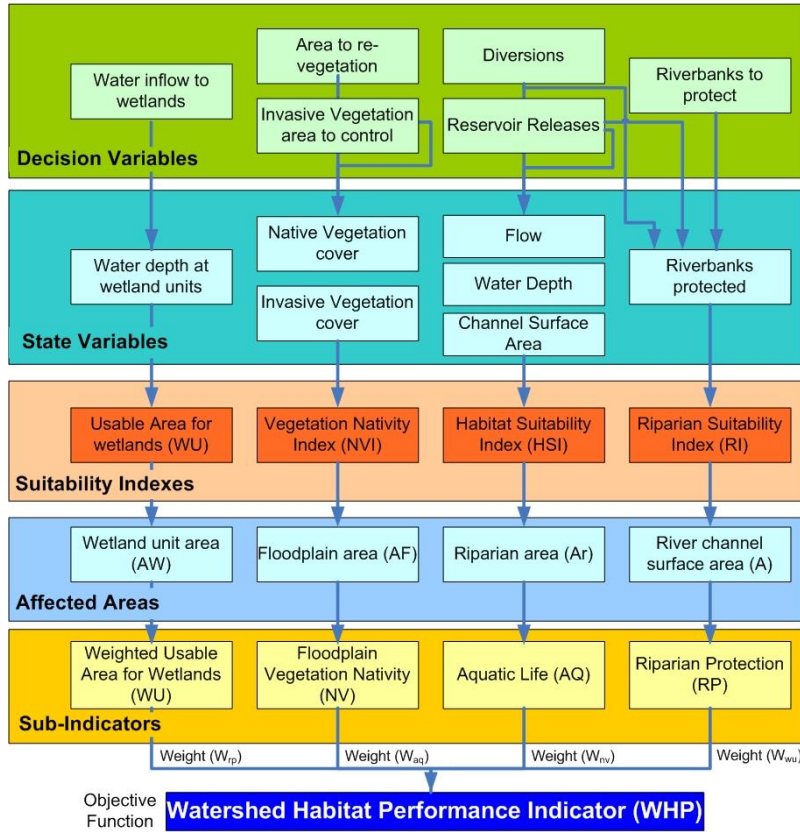


Figure 1. A schematic of the watershed habitat performance optimization model that shows how decision and state variables are connected to the WHP through suitability indexes and affected areas

2.3.3 Floodplain Vegetation Nativity [NV]

Floodplain vegetation [NV (m²)] sub-indicator describes the degree of native vegetation in the floodplain area and is calculated as the product of floodplain area [AF (m²)] and a ratio of native vegetation cover [C_N (m²)] to total vegetation cover [C_V (m²); eq. 6]. The ratio of C_N to C_V also represents the Floodplain Vegetation Nativity Index [NVI (unitless)] which represents the relative area covered by native vegetation to the total vegetation area. NVI takes the value of 1 if all vegetation cover in the floodplain is native and the value of 0 if all vegetation cover is nonnative. C_N and C_V can be measured by simple rapid assessment methods (e.g. field density measurements) or more complicated assessment (e.g. remote sensing and satellite images).

$$NV_{i,t} = \frac{C_{N_{i,t}}}{C_{V_{i,t}}} \times AF_i, \quad \forall i, t \quad [6]$$

2.3.4 Impounded Wetlands [WU]

Wetlands provide an important and productive habitat for ecosystem services in river systems. Water availability is an important factor for wetland ecosystem health. River managers have successfully managed impounded wetlands by adapting agricultural practices and river flows to secure water needs of wetlands (Yang 2011). In some cases, managers define water rights or set aside water volumes for wetland based on estimated requirements. Although several studies have quantified wetland water requirements (Babbar-Sebens et al. 2013; Nikouei et al. 2012; Yang 2011; Yin and Yang 2013), few developed a systems model to link water availability to wetland habitat suitability. These models are mostly empirical and specific to case studies. Alminagorta et al. (In Review) developed a generic model to measure hydro-ecological performance of impounded wetlands given water availability and other factors. Hydrologic-ecological performance is quantified using a performance metric called Weighted Usable Area for Wetlands [WU (m²)] and is the surface area of the wetland whose hydrologic and ecological attributes can support three priority bird species: (1) black necked stilt (*Himantopus*

mexicanus), (2) American avocet (*Recurvirostra americana*) and (3) tundra swan (*Cygnus columbianus*). Alminagorta et al. quantified the effect of water availability observed between 2004 and 2011 on WU. Accordingly, I developed the relationship between water availability and WU as shown in eq. [7]. In the WHP model, water availability (WA) is determined by measuring flow into the impounded wetlands.

$$WU_{i,t} = wu(WA_{i,t}), \quad \forall i, t \quad [7]$$

2.4 System Constraints

Managers and rivers are bounded by a set of physical, natural, and management constraints. These constraints include maximum storage capacities for existing and proposed reservoirs and water infrastructure. Constraints also include water use requirements such as water diversions for agricultural and municipal uses, return flows from those uses, as well as water released to generate hydropower. Other constraints include water mass balance equations at the reservoirs and river nodes where sum of allocated water is less or equal than the total available water. Finally, there is a limitation on both available water and budget to implement management actions. For brevity, I do not list the constraint equations here. The next section shows the application of this systems model to the LBR, Utah and results that can help improve habitat quality and river restoration process.

3. APPLICATION TO THE LOWER BEAR RIVER

The Lower Bear River (LBR) is the portion of the Bear River watershed from the Utah-Idaho Stateline to the Bear River Migratory Bird Refuge (hereafter, the Refuge; Figure 2). The LBR is essential for sustaining the rapid growth and development in Cache and Box Elder Counties within the basin and outside the basin along the Wasatch Front and Salt Lake City, Utah. The river supplies Utah with nearly 30% of its annual surface water or over 2.5 million m³/year. In addition, the LBR provides habitat to some nationally-listed endangered species such as the Great blue heron and Bonneville cutthroat trout. The LBR riparian and wetland habitat are recognized in the list of the ten most at-risk habitats in Utah's Wildlife Action Plan (Bear River CAP 2008). The river is selected for study because it is highly disturbed with human-caused regulated flow, outflows, diversions, return flows in addition to agricultural and grazing activities that degraded the river's habitat and water and environmental managers want to know how they better allocate scarce water to improve habitat within the watershed. We have been working with the Bear River CAP implementation team and the team has helped to formulate the model by providing inputs to the river's restoration targets in addition to priority species and locations and seasons of concern. We incorporated these inputs in both defining the model's sub-indicators and weights. This section shows an application of the model to the LBR and some preliminary results for one segment of the river where we have established and maintained a monitoring site between August 2012 and May 2013.

3.1 Model Application

We identified hydrologic and ecological problems and target restoration objectives through field visits, stakeholder meetings, and relevant literature. To apply the model, we collected hydrologic and ecological data along the watershed by establishing a total of three monitoring sites: two along the river main stem (Morton and the Confluence) and a site on the Cub River (a major tributary) as shown in Figure 2. Data collected includes flow, stage, cross section, riparian topography, pressure and vegetation cover. The preliminary results are based on data collected for an approximately 1,500 meter segment that includes the Confluence site. We measured the values of the four sub-indicators based on the data collected and our equations and calculated the total WHP for the two time periods.

Riparian Protection: Several riparian protection actions are implemented along the LBR to protect the banks from erosion. Table 1 lists the riparian protection actions that are implemented in the LBR and ranks them according to their effectiveness. These weights are based on expert opinion. Table 1 also lists the types and lengths of river shoreline protected along the river segment which did not change between our two times. We also measured the channel cross section and flow at this site and established a flow-stage relationship. Table 2 lists the results.

Aquatic Life: The Bonneville cutthroat trout (*Onchorynchus clarki utah*) is one of the endangered species at the LBR which is sensitive to changes in water flow regime. Hickman and Raleigh (1982) developed the relationships between habitat suitability curves and river water depth. These curves show that HSI drops below 0.2 for water depth of less than 20 cm and reaches the optimum value of 1 at a depth of 45 cm and above. We are using these relationships to measure HSI for Bonneville cutthroat trout based on the changes in water depth as shown in Table 2.

Floodplain Vegetation Nativity: We measured floodplain native and nonnative vegetation cover using simple rapid assessment tools. While paddling along the river, we observed both number of different types of vegetation along the floodplain area (i.e. native and nonnative) and the vegetation cover (i.e. abundant, scattered and scarce). This qualitative assessment is translated into the NVI as shown in Table 2. We delineated and measured the floodplain area for the river segment using DEM maps of a resolution of 1/9 arc-second (approx. 3 meters) using ArcMap 10.2

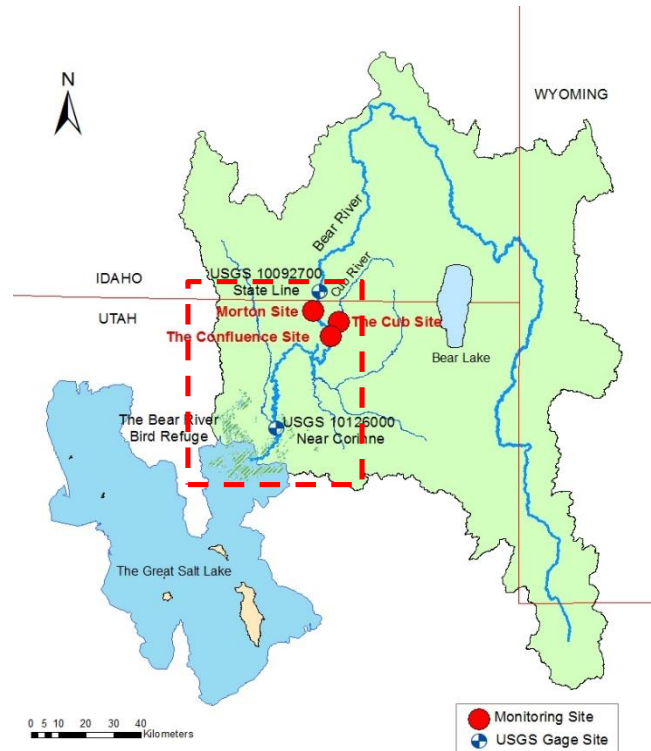


Figure 2. The Bear River watershed and major tributaries. Dashed red box shows the boundary of study area. Red points show the three monitoring sites along the Bear and the Cub Rivers.

Table 1. List of riparian protection actions implemented on the Lower Bear River and their rating weights according to their effectiveness in addition to protected length at the river segment

No.	Riparian Protection Action	Rating weight	Length protected (m)
1.	Land conservation program	0.4	0
2.	Land Easement	0.3	200
3.	Fencing livestock	0.2	600
4.	Erosion control using mulch, blankets or riprap	0.1	0

Impounded Wetlands: The LBR feeds the 300 km² Refuge. We developed the relationship between water availability and WU as shown in Figure 3 based on data from Alminagorta et al. We obtained water inflow from the United States Geological Survey station (10126000 near Corinne, UT) that is located just above the Refuge as shown in Figure 2.

3.2 Results

The four sub-indicators were summed assuming that they all have equal weights of one (i.e. no preference for one indicator over another one has been assumed). This was done to examine the individual contribution of each sub-indicator to the total value of WHP. The results in Table 2 show that the watershed performs slightly better (7%) in May 2013 than in August 2012. The large changes (%) in decision variables and state reflect relatively small changes sub-indicators. This is particularly noticed when the affected area is large enough to overshadow small changes in state variables. This calls for smaller segmentation of the watershed area to

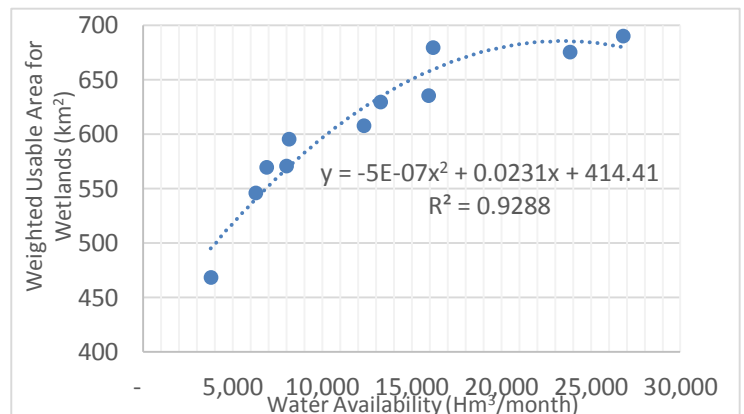


Figure 3. Relationship between water availability and Weighted Usable Area for Wetland. Data from Alminagorta et al. (In Review)

augment the effect of changes in decision variables. For example, although a large increase of water inflow to the Refuge (283% increase) exists in May, the small decrease of flow and water depth at the study site (the confluence) significantly affected the overall watershed habitat performance. The results show that channel width is an important factor in the value of both AQ and RP sub-indicators. In addition, water available to the Refuge in May has increased the value of WU. Therefore, flow is an important decision variable in quantifying habitat quality. The WHP model helps managers understand the potential impacts of their decisions (i.e. reservoir releases) on the watershed habitat quality.

Table 2. Results of applying the WHP model at one river segment over two time periods

Decision and State Variables	August 2012	May 2013	Change (%) from August to May
- Instream flow (Q) (Hm ³ /month)	57	41	-28%
- River width (m)	28	30	7%
- River depth (m)	2.30	1.95	-15%
- Floodplain area (AF) (228m width) (km ²)	31	31	0%
- Inflow to the Refuge (AW) (Hm ³ /month)	9,087	34,820	283%
Suitability Indexes			
- Riparian Suitability Index (RI)	0.07	0.07	0%
- Aquatic Life Suitability (HSI)	1	1	0%
- Floodplain Vegetation Nativity Index (NVI)	0.44	0.44	0%
Sub-Indicators			
- Riparian Protection (RP) (km ²)	2,659	2,891	9%
- Aquatic Life (AQ) (km ²)	37,940	40,650	7%
- Floodplain Vegetation Nativity (NV) (km ²)	14	14	0%
- Weighted Usable Area for Wetlands (WU) (km ²)	583	613	5%
Total Watershed Habitat Performance (WHP) (km²)	41,196	44,168	7%

4. FUTURE WORK

This is an ongoing project. The WHP value and its four sub-indicators will be determined for all river segments along the watershed. We will segment the LBR based on hydrologic changes (i.e. inflows, return flows, diversions) and management needs (i.e. areas of high ecological priority such as oxbow wetlands). We will introduce weights to the four sub-indicators before aggregating them so that spatial, temporal and species priorities are addressed according to management needs. For example, Bonneville cutthroat requires at least 30 cm for instream water to survive during summer months. Therefore higher weights will be assigned to the aquatic life sub-indicators at river segments of concerns during summer months. The values of these weights are set to reflect expert and stakeholder opinion. Finally, the optimization model will be coded using the General Algebraic Modeling System (GAMS) (Hozlar 1990) to recommend best allocation of water and financial resources to improve habitat quality in the four areas of riparian protection, aquatic life, flood vegetation, and impounded wetlands. The model will also be further discussed with the Bear River CAP team and relevant stakeholders to tailor the model weights to serve and support current efforts to restore the river's habitat. In addition, we will explore and apply uncertainty analysis to develop confidence intervals for our performance indicators to show the range of certainty in our results.

5. CONCLUSION

This paper introduces a new Watershed Habitat Performance (WHP) indicator that we use to measure habitat quality at the watershed scale. Embedding this indicator in a systems model helps to recommend ecologic, hydrologic and management actions to allocate scarce resources to improve watershed habitat quality. These actions include alteration of flow, protecting riparian areas from eroding, re-vegetating floodplain area and controlling nonnative vegetation growth. Performance is defined by four common areas of restoration within a watershed: aquatic life, riparian area, floodplain zone and impounded wetlands and their associated sub-indicators. These sub-indicators are summed together with weights that vary spatially and temporally and are based on expert opinion. The results at one river segment emphasize the significant of managing river flow (i.e. through reservoir releases) in order to improve habitat quality. The model helps to rethink the process of quantifying river habitat quality at the

watershed scale by supporting managers and practitioners with tools to help allocate scarce natural and financial resources to improve and restore the river's habitat. The model encourages participatory approach by including stakeholders in the defining of watershed habitat performance indicators and selecting and adjusting of different weights among the indicators.

6. ACKNOWLEDGEMENTS

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