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Abstract

To improve river habitat, managers need to define priority species and their response to changes in flow regimes and then manage infrastructure to allocate water between competing environmental users. We present a new systems optimization model that formulates an ecological objective as aquatic, floodplain, and wetland habitat area to measure in observable units (area). We embed this habitat area metric in a systems model as an objective to maximize. We applied our model to the Lower Bear River watershed, UT. Results show that the Little Bear River, a tributary to the Bear River, has the most potential to increase the watershed habitat performance, particularly between August – December. Increasing Little Bear's reservoirs winter releases and minimizing spring spill volumes can create additional suitable habitat area without harming human users. Our results are displayed on an open-access webmap that allows stakeholders to visualize opportunities to manage water and improve habitat quality.

Keywords	Systems models; River habitat quality; Reservoir operations; Ecological restoration; Watershed management; Web mapping application

Corresponding Author	Ayman Alafifi
Corresponding Author's Institution	Utah State University
Order of Authors	Ayman Alafifi, David Rosenberg

Suggested reviewers	Samuel Sandoval-Solis, Scott Steinschneider, Linda M. Holz

Submission Files Included in this PDF

File Name [File Type]

CoverLetter.docx [Cover Letter]

WASH_Paper.pdf [Manuscript File]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

Research Data Related to this Submission

Data set https://github.com/ayman510/WASH

Repository for source code and data

GitHub repository for all codes used in developing the optimization model (GAMS), input data files (MS Excel), and plotting codes (R). The repository also includes a link for the web mapping application that we developed to share and communicate the results of our modeling effort to our stakeholders.

Dr. Ames,

Please find enclosed our manuscript for the *"Systems Modeling to Improve River, Riparian, and Wetland Habitat Quality and Area"* research article. We have included in the manuscript a section for the software and data availability. We acknowledge the National Science Foundation (NSF) grant #1149297 for supporting this work.

We look forward to receiving the reviewers' feedback.

Thank you

Ayman Alafifi (corresponding author)

Dr. David E. Rosenberg

Department of Civil and Environmental Engineering,

Utah Water Research Laboratory,

Utah State University, Logan, UT, USA 84341

Systems Modeling to Improve River, Riparian, and Wetland Habitat Quality and Area

Authors

Ayman H. Alafifi[1] and David E. Rosenberg[2]

[1]*Corresponding Author:* PhD Candidate Department of Civil and Environmental Engineering and Utah Water Research Laboratory, Utah State University, Logan, UT, USA
aafifi@aggiemail.usu.edu. Phone: +1(435)881-0541, Fax: +1(435)797-1185

[2]Associate Professor, Department of Civil and Environmental Engineering and Utah Water Research Laboratory, Utah State University, Logan, UT, USA david.rosenberg@usu.edu

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Highlights

- A systems model to maximize a physically measurable ecological objective, habitat area
- The model suggests water and money allocations to improve river, floodplain, and wetland habitats
- The model identifies sites and times where managers can most improve habitat using scare water, money, and planting efforts without harming human uses
- The model recommends reducing Little Bear River reservoir spring spills and increase winter releases to improve habitat quality
- An open web map facilitates communication with stakeholders

Software and Data Availability

Name of software:	Watershed Area of Suitable Habitat (WASH) optimization model
Developers:	Ayman H. Alafifi and David E. Rosenberg
Contact:	aafifi@aggiemail.usu.edu
Year first available:	2016
Hardware required:	A personal computer
Software required:	General Algebraic Modeling System software (GAMS) with non-linear global solver such as Branch-And-Reduce Optimization Navigator (BARON), MS Excel 2016, R 3.3.0, and a web browser
Software availability:	All source code, input data, post-processing file, and documentation are available on Alafifi (2017). The application of WASH to the Lower Bear River, Utah for one year (2003) is displayed on an open-access web map at: https://www.WASHmap.usu.edu
Cost:	The source code is released under the GNU General Public License v2.0, which allows for reuse of the code.

Systems Modeling to Improve River, Riparian, and Wetland Habitat Quality and Area

1. Introduction

Rivers and their riparian and wetland areas are managed for many services such as domestic and agricultural water supply, hydropower generation, flood damage reduction, and habitat for flora and fauna (Bernhardt et al., 2005). Although human uses can degrade river ecosystem functions, there are also opportunities to improve habitat (Jager and Smith, 2008; Tharme, 2003). Improving river habitat requires defining measureable ecological objectives and deciding the timing, magnitude, and locations of reservoir releases, diversions, and planting efforts to advance those objectives.

These timing, magnitude, and location decisions are difficult because managers must first identify which of the numerous watershed aquatic, floodplain, and wetland assets to target for improvement. Second, managers must select indicator species whose presence denotes healthy ecosystems, abundance can be monitored, and are directly impacted by flow conditions. Third, managers must mathematically quantify each species' response to changes in flow regimes. And finally, managers must collaborate with watershed stakeholders to identify when, where, and how to manage water and plants to improve habitat over observed conditions (Barbour et al., 2016).

Some quantification approaches such as the natural flow paradigm define species hydrologic requirements to mimic important timing, duration, magnitude, and frequency features of the natural flow regime (Poff et al., 1997). These approaches assume that historical natural flows are known and adequate to create desired ecosystem functions (Baron et al., 2002). Other approaches such as habitat quality indexes relate flow alternations to habitat conditions. These relationships describe the suitability of habitat to promote the survival and productivity of a single species. Index values vary from 0 (poor) to 1 (excellent) and are based on single or multiple habitat attributes such as instream water depth, water temperature, substrate, etc. (Hemker et al., 2008; Hooper, 2010; Pinto et al., 2009). For example, the Habitat Suitability Index (HSI; U.S. Fish and Wildlife Service 1981) is an ecological habitat quality index used to estimate the effects of water flow reduction on fish populations (e.g. IFIM; Stalnaker, 1995), relate hydraulic physical habitat to ecological services (e.g. HEC-EFM; Hickey and Fields, 2013), and define environmental flows for priority species (e.g. ELOHA; Poff et al., 2010). These unitless indices compare habitat for an individual species across locations under prior or proposed hydrologic regimes, but require additional tools to determine whether regimes are feasible and where and when to invest water, money, and effort to improve multiple habitat types across a watershed.

Water resources systems models can determine the feasibility of a proposed hydrologic regime by including multiple ecosystem assets as part of a connected network of reservoir, river, tributary, diversion, demand, and return flow components. Models often include one or more habitat suitability indexes as a constraint such as a minimum required instream flow to satisfy (see, for example, Cioffi and Gallerano, 2012; Harman and Stewardson, 2005; Porse et al., 2015; Ryu et al., 2003). In other cases, the suitability index is optimized as a single objective or tradeoff with water delivery, hydropower generation, or other objectives (Null et al., 2014; Simonović and Nirupama, 2005; Yang, 2011). Typically, systems models define ecosystem objectives as a penalty to minimize deviations from a pre-defined target value. For example, Higgins et al. (2011) developed a heuristic nonlinear integer optimization model to minimize the difference between ecological response functions that derive from managed and natural flow regimes in the Murray River, Australia. Steinschneider et al. (2014) used linear programming to minimize the deviation between model recommended reservoir releases and estimated natural flows in the Connecticut

River basin. And in the Murray River, Szemis et al. (2012, 2014) developed a heuristic ant colony nonlinear model to minimize the inverse of an ecological index plus constraint violations. Minimizing deviations from a target poses challenges such as managers must subjectively define the target as a natural or species-required flow (Barbour et al., 2016). Also, deviations and indexes do not have physical meaning and are difficult to measure, validate, communicate, or compare across watershed sites.

This paper develops a measurable, observable habitat area metric measured in acres and embeds the metric in a Watershed Area of Suitable Habitat (WASH) systems model as an ecological objective to maximize. The WASH model and habitat area objective allow managers to (i) compare ecological measures across sites, (ii) identify where and when to apply scarce water, money, and planting efforts to most improve habitat quality and area, (iii) involve stakeholders to help define ecological objectives, view, and validate results, and (iv) adapt the method to other basins, sites, habitat types, and species. Below, section 2 describes the model formulation and system components. Section 3 introduces a case study for the Lower Bear River, Utah. The remaining sections present results, discuss management implications, and conclusions.

2. Methods

Improving river habitat quality and area requires a collective effort among researchers and managers to identify ecosystem functions, habitat types, indicator species, suitability of habitat for species, and the network of ecosystem and other water system components. Here, we demonstrate a participatory approach to develop a systems model that maximizes habitat, addresses multiple habitat management goals, and identifies promising management strategies to improve habitat quality and area.

This participatory approach started by soliciting support from managers and stakeholders when the project was proposed. Subsequently, we worked with stakeholders on related efforts to develop a conservation action plan (Bear River CAP, 2008) for the watershed and inventory existing information for select sub-watersheds (Bio-West, 2015). During this work, it became clear that a systems model must have a physically measureable, observable objective function that considers habitat quality and area so managers can compare habitat across diverse ecological sites, communicate results, and show implications of actions over time.

To address habitat quality, we designed suitability indexes [unitless] for aquatic, floodplain, and impounded wetland habitats as functions of hydrologic and ecological variables such as water depth, flood recurrence, and plant cover (Figure 1). These functions are reach-, species-, and life stage- dependent. We multiply each suitability index by an affected area to give a habitat indicator measured in real area units (e.g. m^2). Affected areas are also functions of flow and plant cover variables. We aggregate habitat indicators using spatial and temporal weights to express the overall WASH area for the watershed in area units (also m^2). We then embed the objective function in a network of nodes (demand sites, reservoirs, and junctions) and links (river reaches, diversions, and return flows; see Appendix A, Figure A.1) that have attributes as shown in Figure 1.

Below we describe the general model formulation of decision variables, objective function, and constraints.

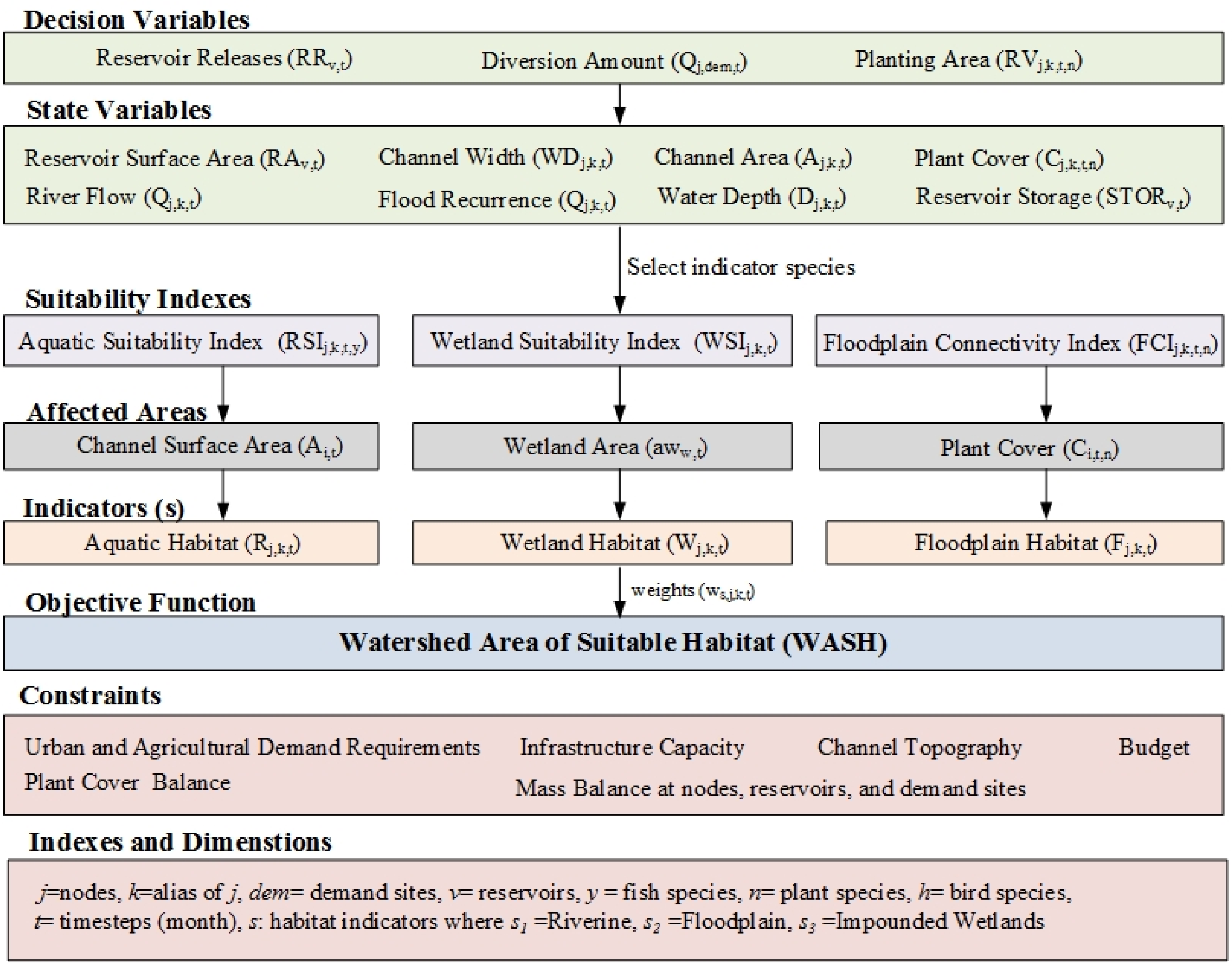

Figure 1. The WASH model connects decision variables, state variables, parameters, and suitability indexes to an objective function measured as habitat area. Physical, management, and plant constraints limit decisions

In the formulation, capitalized terms represent variables, lower case indicates parameters and model inputs, and lettered subscripts denote indices for space, time, species, and habitat types (bottom of Figure 1). We selected a monthly time step (*t*) because watershed managers plan and schedule flow management actions at monthly intervals. Fish spawning, seed recruitment, migratory bird feeding, nesting, and breeding also occur at that time scale.

2.1. Decision Variables

To improve habitat quality, managers can adjust reservoir releases $RR_{v,\mathrm{t}}$ [million cubic meters per month, Mm^3] at reservoir v in month t. They also control diversions volumes $Q_{\mathrm{j,dem,t}}$ [Mm^3/month] from the river at node j to demand sites dem in month t to satisfy urban and agricultural demand. Managers can also plant $RV_{j,\mathrm{k,t,n}}$ [Mm^2] the floodplain adjacent to the river reach from node j to node k during month t by seeding or planting species n. These variables control a group of state variables that include reservoir storage volume $STOR_{v,\mathrm{t}}$ [Mm^3], reservoir surface area $RA_{v,\mathrm{t}}$ [Mm^2], river flow $Q_{j,\mathrm{k,t}}$ [Mm^3/month] from node j to node k in month t, river water depth $D_{j,\mathrm{k,t}}$ [m/month], channel surface area $A_{\mathrm{j,k,t,}}$ [Mm^2], channel width $WD_{j,\mathrm{k,t}}$ [m], and floodplain plant cover $C_{j,\mathrm{k,t,n}}$ [Mm^2].

2.2. Objective Function

The WASH objective function maximizes the weighted sum of the suitable areas of aquatic [$IND_{aquatic,j,k,t}$], floodplain [$IND_{floodplain,j,k,t}$], and wetland [$IND_{wetland,j,k,t}$] habitats [Mm^2] in reach j to k in month t where $wght_{s,j,k,t}$ are the stakeholders-decided weights for habitat indictor s in reach j to k at month t. Weights take values from 0 (not important) to 1 (important).

$$Max\ \ WASH = \sum\nolimits_{s,j,k,t} wght_{s,\mathrm{j,k,t}} \cdot \ IND_{s,j,k,t} \qquad \text{-- [1]}$$

The value of each habitat indicator is the product of a suitability index and an affected area. Suitability indexes (*SIs*) are functions of the habitat attribute(s) that influence priority species survival and abundance. Values of SIs approach 1 (excellent conditions) when priority species exist (or their density exceeds a certain threshold). In contrast, *SIs* tend towards 0 (poor conditions) when priority species do not live or their density is below a threshold (Roloff and Kernohan, 1999). SIs are constructed using empirical data, or absent data, they are assigned based on expert opinion.

2.2.1. Aquatic Habitat

Managers can improve fish habitat by improving the flow regime that shapes physical habitat health and determines biotic composition of riverine species (Bunn and Arthington, 2002). Here, we use water depth and temperature as two primary abiotic factors that define aquatic habitat quality and suitability for fish (Jackson et al., 2001). We designed site-, species-, and life stage-specific water depth suitability curves and adjust them to the water temperature tolerance of fish species. Where water temperature is the limiting factor, the poor value for habitat suitability curves is the water depth observed at the warmest time of the year under study. The aquatic habitat indicator is calculated by multiplying the Aquatic Suitability Index (*rsi*; unitless) and channel surface area (Eq. 2). With multiple fish species (*y*), we multiply suitability indexes together to emphasize the concurrent need for suitable water depths for all species at the same time and location.

$$IND_{aquatic,j,k,t} = \prod_{y} rsi_{j,k,t,y}(D_{j,k,t}) \cdot A_{j,k,t}\,, \qquad \forall\, j,k,t \qquad \text{---- [2]}$$

Other methods to combine multiple species use arithmetic or geometric averages to aggregate multiple indexes and assume that good habitat for one species compensates for poor condition for another species (Ahmadi-Nedushan et al., 2006).

2.2.2. Floodplain Habitat

Floodplains are areas adjacent to streams and are periodically inundated with water. Floodplains are characterized by a seasonally high water level that inundates riparian plant roots and keeps soil moist (Meier and Hauer, 2010). The lateral connectivity between the river channel and its floodplain area is a primary factor shaping plant communities' composition, abundance, and survival (Merritt et al., 2010; Poff et al., 1997; Rivaes et al., 2013; Rood et al., 2005). Connected floodplains means that plant recruitment and seed germination coincide with flood events that occur when discharge exceeds the bankfull flood level (Meier and Hauer, 2010; Yarnell et al., 2010). Bankfull flood level is defined at a visible break in slope between the un-vegetated bank and adjacent vegetated floodplain surface (Li et al., 2015; Parker et al., 2007). Bankfull discharge is reported to occur, on average, every 1 to 2 years (Dunne et al., 1978; Harman and Jennings, 1999; Leopold et al., 1964) and is often associated with the 1.5 year flood recurrence interval (Kilpatrick and Barnes, 1964; NOAA, 2015; Rosgen, 1994). Restoring lateral connectivity to floodplain habitat requires managing flow to exceed the 2-year inundation level discharge during the seed germination season of target riparian plants.

The floodplain connectivity indicator is calculated by multiplying a floodplain connectivity index (fci) by the area of plant cover (*C*) for each month *t* and then summing the values for each plant species *n* [eq. 3]. fci is a function of streamflow and takes the value of 1 [excellent lateral connectivity] if the instream flow $Q_{j,k,t}$ equals or exceeds the 2-year recurrence flow. fci takes the value of 0 [poor connectivity] when flow is at or below the 1-year recurrence value. The 1- and 2-year recurrence flow thresholds are determined from historical flow records using the Log Pearson Type III distribution with mean and standard deviation of the log-transformed annual flow series. The summation in eq. [3] emphasizes that individual plant species can exist at different distances from the river bank and require different flood magnitudes to establish connectivity.

$$IND_{floodplains,j,k,t} = \sum_n fci_{j,k,t,n}(Q_{j,k,t}) \cdot C_{j,k,t,n} \qquad \forall\, j,k,t \qquad \text{----[3]}$$

2.2.3. Impounded Wetlands

Wetlands are recognized as one of the most productive ecosystems for a variety of wildlife species, particularly waterbirds (Nikouei et al., 2012). Maintaining and managing wetland ecological services requires understanding the water depth and plant cover habitat characteristics different bird species use to feed, nest, rest, and breed (Downard and Endter-Wada, 2013; Faulkner et al., 2010; Rogers and Ralph, 2011). The Wetland Suitability Index (*wsi*) of WASH represents the suitability of impounded wetlands to improve water depth and native plant cover for priority bird species. Here, impounded wetlands have dikes, gates, weirs, canals, or other hydraulic structures that allow managers to control flows into and out of wetlands. Within impounded wetlands, *wsi* relationships for different bird species can be established from literature reviews, expert opinion, or derived from other models (e.g. Alminagorta et al., 2016). In Eq. [4], we use *WSI* to define an aggregate index that describes the suitability of water depth and native plant cover for multiple wetland bird species. The impounded wetland indicator is calculated by multiplying a *wsi* index by the total wetland surface area *aw* [Mm^2].

$$IND_{wetlands,j,k,t} = WSI_{j,k,t}\left(Q_{j,k,t}\right) \cdot aw_{j,k,t}, \qquad \forall\, j,k,t \qquad \text{----- [4]}$$

2.3. Constraints

Reservoir release, diversion, planting, and other decisions are bound by physical [eqs. 5-13], infrastructure [eqs. 14], and management [eq. 15-17] constraints.

a. **Reservoir storage balance**. A low-order, finite-difference mass balance requires that reservoir storage for each reservoir *v* at the beginning of each time step *t+1* equal storage at the beginning of prior time step *t* plus net flows of links leading to the reservoir minus reservoir releases and minus evaporation losses [eq. 5]. Reservoir releases are flows along all links that leave reservoir *v* in month *t* [eq. 6]. Evaporation losses are estimated by multiplying a monthly evaporative rate $evap_{v,t}$ [m/month] by the reservoir surface area. $RA_{v,t}$ is a function of reservoir storage. The term $lss_{j,v,t}$ [%] is the net loss rate on links connecting to reservoir *v* and is expressed as a fraction of link flow.

$$STOR_{v,t+1} = STOR_{v,t} + \sum_j [Q_{j,v,t} \cdot (1 - lss_{j,v,t})] - RR_{v,t} - [evap_{v,t} \cdot RA_{v,t}(STOR_{v,t})] \; \forall v,t \quad \text{-- [5]}$$

$$RR_{v,t} = \sum_j Q_{v,j,t} \quad \forall v,t \quad \text{----- [6]}$$

b. **Mass balance at junctions**. Flows entering each non-reservoir node *j* must equal or exceed evaporative losses plus flows leaving the node [eq. 7]. $localInflow_{j,t}$ [Mm^3/month] are reach gains, groundwater inflows, or other flows that accumulate at node *j* in time *t*. At the most upstream nodes in a network, *localInflow* is the head flow and represents the boundary condition and cumulative contribution of climate, runoff, and other hydrologic processes. *linkEvap* [m/month] describes the evaporative loss rate on links; link evaporation [m^3/month] is the product of the evaporative loss rate and channel surface area.

$$localInflow_{j,t} + \sum_k Q_{k,j,t} \cdot (1 - lss_{k,j,t}) - \sum_k A_{k,j,t} \cdot linkEvap_{k,j,t} \geq \sum_k [Q_{j,k,t}] \; \forall j,t \quad \text{---[7]}$$

c. **Mass balance at each demand site**. Total flow to each demand site *dem* in time *t* must equal or exceed the return flow back to the river [eq. 8]. Total flow is reduced by the depleted flow amounts that include diversion losses $lss_{k,dem,t}$ and urban or agricultural consumptive use fraction $Cons_{k,dem,t}$ [both % of inflow received].

$$\sum_k Q_{k,dem,t} \cdot (1 - lss_{k,dem,t}) \cdot Cons_{dem,t} \geq \sum_k Q_{dem,k,t} \quad \forall dem,t \quad \text{---- [8]}$$

d. **Plant cover**. Plant cover $C_{j,k,t,n}$ [Mm^2] for each species *n* in each link *j* to *k* at time step *t* equals cover at prior time step *t-1* plus planted areas $RV_{j,k,n}$ [Mm^2] and natural growth or death $g_{j,k,n}$ [Mm^2; eq. 9]. Plant cover $C_{j,k,t,n}$ cannot exceed the total floodplain area adjacent to each reach $cmax_{j,k}$ [eq. 10]. Planting $RV_{j,k,n}$ is also limited to growing season [eq. 11]

$$C_{j,k,t,n} = C_{j,k,t-1,n} + RV_{j,k,t,n} + g_{j,k,n} \quad \forall j,k,t,n \quad \text{---- [9]}$$

$$\sum_n C_{j,k,t,n} \leq cmax_{j,k} \quad \forall j,k,t \quad \text{---- [10]}$$

$$\sum_n RV_{j,k,t,n} \leq \begin{cases} cmax_{j,k}, & t \in growing\ season \\ 0, & otherwise \end{cases} \quad \forall j,k,t \quad \text{---- [11]}$$

e. **Channel topology relationships**. River flow, channel stage, width, and surface area are related on each link j to k in each time step t [eqs. 12-14]. These relationships are established based on measured data. We use linear relationship for stage-flow (sf) and Leopold and Maddock (1953) power function for width-flow (wf) relationships. $lng_{j,k}$ is the length of each river segment [m].

Stage-flow relationships: $D_{j,k,t} = sf_{1j,k} \cdot Q_{j,k,t} + sf_{2j,k}$ $\quad \forall\, j,k,t$ ---- [12]

Width-flow relationships: $WD_{j,k,t} = wf_{1j,k} \cdot \left(Q_{j,k,t}\right)^{wf_{2j,k}}$ $\quad \forall\, j,k,t$ ---- [13]

Channel surface area: $\mathrm{A_{j,k,t}} = WD_{j,k} \cdot lng_{j,k}$ $\quad \forall\, j,k,t$ ---- [14]

f. **Reservoir storage limits.** Storage in each reservoir *v* cannot go below a minimum storage volume $minstor_v$ [Mm^3] or exceed storage capacity $maxstor_v$ [Mm^3] at any time *t* [eq. 15].

$$minstor_v \leq STOR_{v,t} \leq maxstor_v \quad \forall v,t \qquad \text{---- [15]}$$

g. **Meet demand requirements**. Diversions to each demand site *dem* should meet requirements $dReq_{dem,t}$ [Mm^3/month] in each time *t* [eq. 16].

$$\sum_k Q_{k,dem,t} \cdot (1 - lss_{k,dem,t}) \geq dReq_{dem,t} \quad \forall dem,t \qquad \text{--- [16]}$$

h. **Flow limits**. Minimum and maximum values $qmin_{j,k,t}$ and $qmax_{j,k,t}$ bound flow in each link *j* to *k* in time *t* [eq. 17]. Minimum levels may be minimum instream flow or diversion requirements. Maximum bounds can be channel, diversion, or other capacities.

$$qmin_{j,k,t} \geq Q_{j,k,t} \geq qmax_{j,k,t} \quad \forall j,k,t \qquad \text{---- [17]}$$

i. **Management budget**. The total cost to plant floodplain species [ct_n; \$/m^2], make reservoir releases, or adjust diversion gates [st_n; \$/m^3] should not exceed the financial budget *b* [\$; eq. 18].

$$\sum_j \sum_k \sum_n \sum_t (ct_n \cdot RV_{j,k,t,n}) + \sum_j \sum_j \sum_t (st_{j,k,t} \cdot Q_{j,k,t}) \leq b \qquad \text{------[18]}$$

Nonlinear functions in Eqs 2-4, 5, and 7 are all continuous and smooth to avoid numerical difficulties in the optimization. The nonlinear systems model maximizes the WASH habitat area in eq. [1] subject to constraints [2] through [18]. Section 3 shows an application of WASH systems model to the Bear River, Utah and the recommendations to improve habitat quality and area.

3. Lower Bear River, UT Case Study

The WASH model is applied to the Lower Bear River from the Utah-Idaho state line to the river's terminus at the Great Salt Lake (Figure 2: red box). This area is part of the longer 491-mile Bear River that starts in Utah, flows north through Wyoming and Idaho, then returns south through Utah to be the largest tributary to the Great Salt Lake. The Utah Division of Water Resources (2004) estimates that approximately 60% of Bear River flow comes from snowmelt runoff in April, May, and June.

We selected this watershed because it is also subject to intensive human disturbance from grazing, agricultural, and urban activities. Some 500 irrigation systems in the basin supply water for half a million acres of land across the three states. The River also supplies numerous cities, communities, and individual families, plus run-of-river hydroelectric plants (Bear River Commission, 2012). The river and its tributaries also support rapid growth and development in Cache and Box Elder Counties, Utah.

At the river's terminus with the Great Salt Lake, the U.S. Fish and Wildlife Service (FWS) manages 300 km^2 of impounded wetlands at the Bear River Migratory Bird Refuge (hereafter the Bird Refuge) to provide feeding, resting, and breeding grounds for several globally significant populations of migratory birds. The Bird Refuge holds a junior water right to upstream agricultural users and most other land in the lower Bear River watershed is privately owned (Downard et al., 2014). Thus, few formal and legal mechanisms exist to provide water and other resources to improve aquatic, floodplain, and impounded wetland ecosystems throughout the basin. Fish barriers, urbanization, water development, and introduction of nonnative species such as cheatgrass (*Bromus tectorum)* and rainbow trout (*Oncorhynchus mykiss*) lead to loss of native species (Bear River CAP, 2008; Bio-West, 2015). These disturbances reduce floodplain connectivity, alter plant community composition, channel shape, and regulated flow hydraulics. The Nature Conservancy, Trout Unlimited, landowners, local, state, and federal agencies have identified low flow and warm water temperatures as major threats to fish populations, riparian plants, and migratory birds (Bear River CAP, 2008). These managers want to know how much water is available in the system for aquatic, riparian, and wetland habitats, and where, when, and how to allocate that water to improve habitat quality and area for priority species.

3.1. Model Input Data

WASH requires hydrologic, ecological, topological, and management data (Table 1). We developed the required data from sources including the Utah Division of Water Resources (DWRe) GenRes water supply/demand simulation model for the lower Bear River (Adams et al., 1992), the USDA National Agriculture Imagery Program imagery (USDA, 2014), the National Hydrography Dataset (USGS, 2012) and its attribute extensions (NHDPlus V2), several USGS gage stations (#10092700, 10126000, 10020100, 10020300, 10093000, 10105900, and 10113500), plus the Utah State University (USU) Little Bear River WATERS Test Bed monitoring sites (UWRL, 2009). We also started two monitoring sites on the Bear River mainstem and one site on Cub River to collect and ground truth hydrologic and ecological data between August 2012 and November 2016. Bird Refuge data and model results were obtained from Alminagorta et al. (2016). A budget of $650,000 was assumed based on the Cache County Water Masterplan estimated budget for future ecosystem projects (JUB, 2013). Processed hydrologic and ecologic data is available at the Bear River Fellows website (http://bearriverfellows.usu.edu) and WASH model input data and code are available at (Alafifi, 2017).

Table 1. Data required for WASH model components

Model Component	Data Item	Source(s)	Component Type
Aquatic Habitat	Reach lengths	NHDPlus V2, field measurements	Link
	Water depth-ecological suitability curves	FWS, stakeholders, and literature	Link
Floodplain Habitat	Plant cover and distance from banks	NAIP Imagery, field measurements	Link
	Floodplain area	NAIP Imagery, field measurements	Link
	Flow-ecological suitability curves	FWS, stakeholders, and literature	Link
Wetland Habitat	Wetland unit water level-storage curves	LiDAR, field measurements	Link
	Invasive plan cover	Landsat satellite imagery	Link
	Evaporation rates	Western Regional Climate Center	Link
	Flow-ecological suitability curves	FWS, stakeholders, and literature	Link
Physical Constraints	Reservoirs storage-elevation-area, evaporation, and capacity	GenRes, U.S. BoR	Node
	Diversions capacity	GenRes	Link
Natural Constraints	Headwater and local inflows	USGS, NHDPlus V2, LittleBear WATERS TestBed	Node
	Water level and channel cross section	Field measurements	Link
	Evaporative losses on reaches	NHDPlus V2	Link
	Natural growth of riparian plants	Stakeholders	Link
Management Constraints	Urban and agricultural demand	GenRes	Node
	Consumptive use of flow	GenRes	Node
	Instream flow requirements	Stakeholders	Link
	Budget and unit costs	Stakeholders	Link
Model Formulation	Weights	Stakeholders	Link

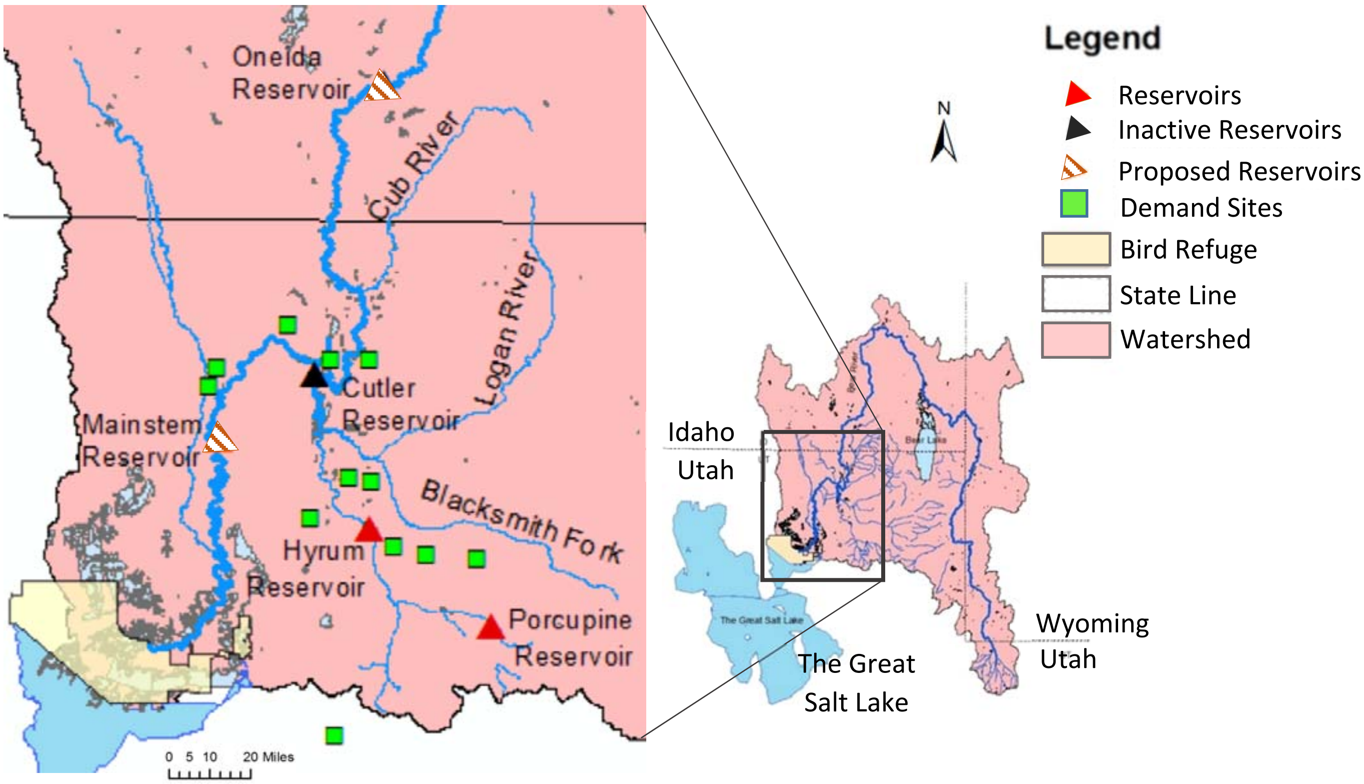

Figure 2. The Lower Bear River Watershed including the reservoirs and demand sites

We segmented the Bear River and its main tributaries into a network of 43 nodes and 56 links with 5 reservoirs, 12 municipal and agricultural demand sites, and 26 environmental sites where species of concern live (Appendix I). We implemented the model and all the scenarios described below in section 3.4 on a monthly time basis for one calendar year (2003) as a representative year that had monthly headflows close to monthly mean flows observed over the last 15 years. We selected a single year to run the model because most reservoir and watershed managers in the basin plan operations at monthly intervals for a one-year cycle. A subsequent scenario extended the model time horizon to 5 years (2003 – 2007) to consider annual variability. We ran the model with the same weight values of 1 for all indicators to avoid favoring a location, species, or month.

3.2. Selection of indicator species

The presence and abundance of indicator species is a strong signal of ecosystem response to alterations in flow regimes (Carignan and Villard, 2002). We identified native and game fish, riparian plants, and wetland bird species in the Lower Bear River watershed in collaboration with stakeholders from the CAP team (Table 2).

Table 2. Habitat indicator components by habitat type, species, species life stage, and ecosystem function.

Habitat	**Indicator Species**	**Life Stage**	**Aspects of life stage supported and (timing)**	**Habitat Attributes**	**Suitable Range of Habitat Attribute**	**Affected Area**	**Data Source(s)**
Aquatic	Bonneville cutthroat trout (*Onchorynchus clarki utah*)	Adult	Native spawning (Sep. – Mar.)	Water depth (m)	0.30 - 0.75	Channel surface area	Hickman and Raleigh (1982), Braithwaite (2011), Gosse et al. (1977) and Gosse (1981)
		Fry	Native maturing (Apr. – Aug.)		0.10 - 0.45		
	Brown trout (*Salmo trytta*)	Adult	Game fish spawning (Sep. – Mar)		0.10 - 0.80		
		Fry	Game fish maturing (Apr. – Aug.)		0.10 - 0.50m		
Floodplain	Cottonwoods (*Populus fremontii* and *P. angustifolia)*	Seed germination & dispersal	Native recruitment (Apr. – Aug)	Flood recurrence	> Bankfull flow	Floodplain area	Meier and Hauer (2010) Mahoney and Rood (1998)
Wetland	Black-necked stilt (*Himantopus mexicanus*)	Adult	Feeding, resting, and breeding (Apr. – Sep.)	Water depth (m)	0.15– 0.25m	Impounded wetland area	Alminagorta et al. (2016)
				Invasive plant cover (%)	< 10%		
	American avocet (*Recurvirostra Americana)*		Feeding, resting, and breeding (Mar. – Oct.)	Water depth (m)	0.35- 0.45m		
				Invasive plant cover (%)	< 10%		
	Tundra swan (*Cygnus columbianus*)		Feeding and resting (Nov.– Mar.)	Water depth (m)	> 0.55m		
				Invasive plant cover (%)	< 10%		

3.2.1. Aquatic Habitat

Bonneville cutthroat trout (BCT; *Oncorhynchus clarki utah*) is a critical native fish species in the Blacksmith Fork and the Little Bear Rivers, two Bear River tributaries, and the target of many restoration efforts by private groups and the Utah Division of Natural Resources. BCT habitat has seen substantial reductions in recent decades (Bio-West, 2015). Brown Trout (*Salmo trytta*) is a non-native, popular game fish because it has high tolerance to low summer flows, warmer lower-elevation reaches, and parasites causing whirling disease compared to other members of the trout family (UtahFishingInfo Website, 2016). The Bear River main stem is at lower elevation and has a warmer summer water temperature that reaches 26^o C. The Little Bear and Blacksmith Fork are higher elevation rivers and have cooler water temperatures that do not exceed 22.5^o C (Watershed Sciences, 2007). Johnstone and Rahel (2003) report that water temperature at or above 25^o C could be lethal for BCT, while Raleigh et al. (1984) reported that brown trout can tolerate water temperature up to 27.2^o C. Currently, BCT is only abundant in the headwaters of the Blacksmith and Little Bear Rivers (DeRito, pers. comm., 2016). Thus, we assigned BCT as the indicator fish species in headwaters reaches and brown trout on remaining reaches.

We developed aquatic suitability index (*rsi*) curves that vary between values of 0 at water depths that empirical studies found no fish and 1 at water depths were fish (or red counts) where abundant. The corresponding water depth ranges were drawn from a 2-year study in the nearby Strawberry River for BCT by Braithwaite (2011) and for brown trout from Gosse et al. (1977) and Gosse (1981) on the Logan and Provo rivers in northern Utah. Note, for brown trout, we assign a poor suitability index value of 0 at 10cm water depth because brown trout can tolerate very shallow depths (Raleigh et al., 1984). We used Boltzmann and exponential decay functions to develop suitability index curves for BCT and brown trout (Figure 3) based on the curve shapes of the FWS HSI for water depth (Hickman and Raleigh, 1982; Raleigh et al., 1984) .

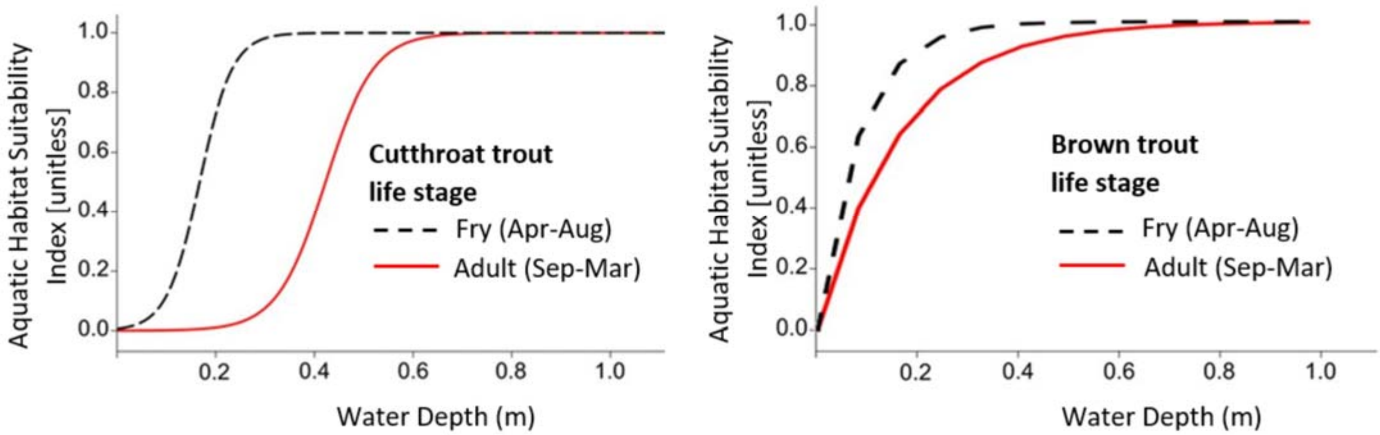

Figure 3. Aquatic Suitability Index values for water depth for bonneville cutthroat trout (left) and brown trout (right).

3.2.2. Floodplain habitat

We selected cottonwood trees (*Populus fremontii* and *P. angustifolia*) as an indicator native plant species because it predominates the floodplains in the Lower Bear River and provides shade, food, and habitat for mammals, birds, and insects. Cottonwoods release seeds just after peak flows in snowmelt-driven rivers (Bhattacharjee et al., 2006; Mahoney and Rood, 1998). Thus, lateral connectivity between the channel and floodplains is mostly needed between April and June for successful seed dispersal and then through August for continued soil moisture to establish dispersed seeds (Bhattacharjee et al., 2008; Mahoney and Rood, 1998). Cottonwood trees grow adjacent to river channels and will likely be inundated by flow magnitudes over bankfull flow (1.5-year flood recurrence value). Therefore, floodplain connectivity curves transition from 0 (poor) to 1 (excellent) between flow values with recurrence interval of 1- and 2-years (Figure 4). We measured initial existing cottonwood tree cover alongside every reach from NAIP Imagery.

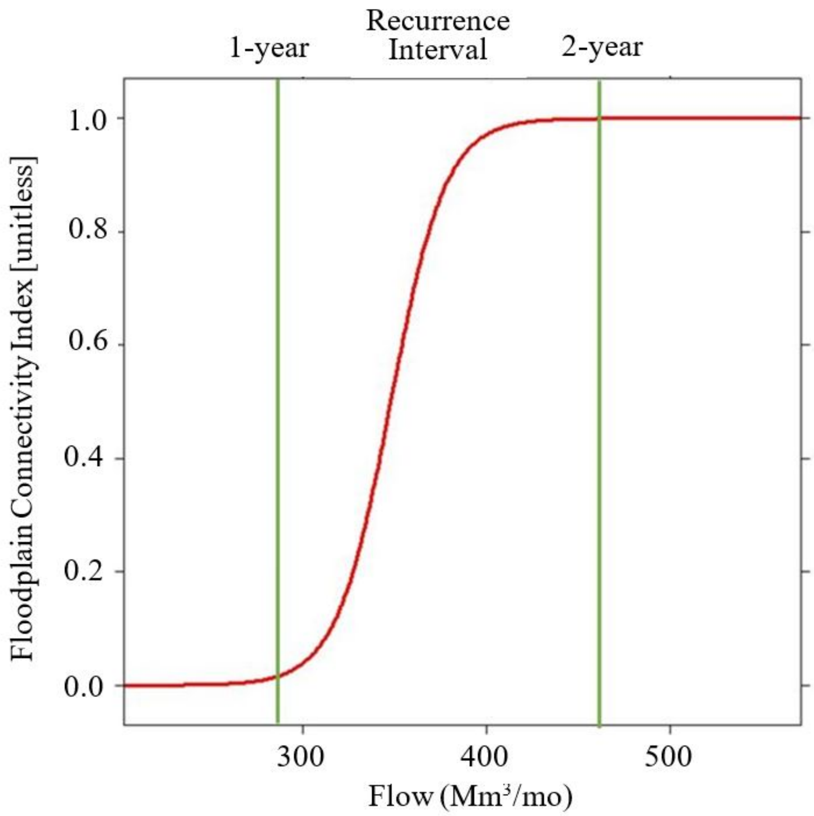

Figure 4. Floodplain connectivity index as a function of flow at the Bear River Corinne site. Floodplain suitability transitions from 0 to 1 between flow values with recurrence interval of 1- and 2-years

3.2.3. Impounded wetland habitat

The Bird Refuge comprises 25 diked wetland units that draw water from the Bear River and provide resting, feeding, and breeding area for 200+ migratory bird species throughout the year (Downard et al., 2014). Prior work by Alminagorta et al. (2016) developed a composite Usable Area for Wetland (WU) metric for the Refuge (measured in m^2) and used it in a systems model to maximize the wetland surface area whose water depth and plant cover characteristics support Black-necked stilt, American avocet, and Tundra swan (Table 2). These three priority bird species were selected because they use a range of shallow, medium, and deep water depths that encompass depths used by 20 other priority bird species at the Refuge. Here, we estimated monthly wetland suitability index values by dividing Alminagorta's (2016) monthly WU areas generated for various water availability scenarios between 1992 to 2011 by the total Refuge area. Then we developed monthly relationships between the suitaibilty index values and monthly river flows measured at the Corinne, UT USGS station (one example in Figure 5).

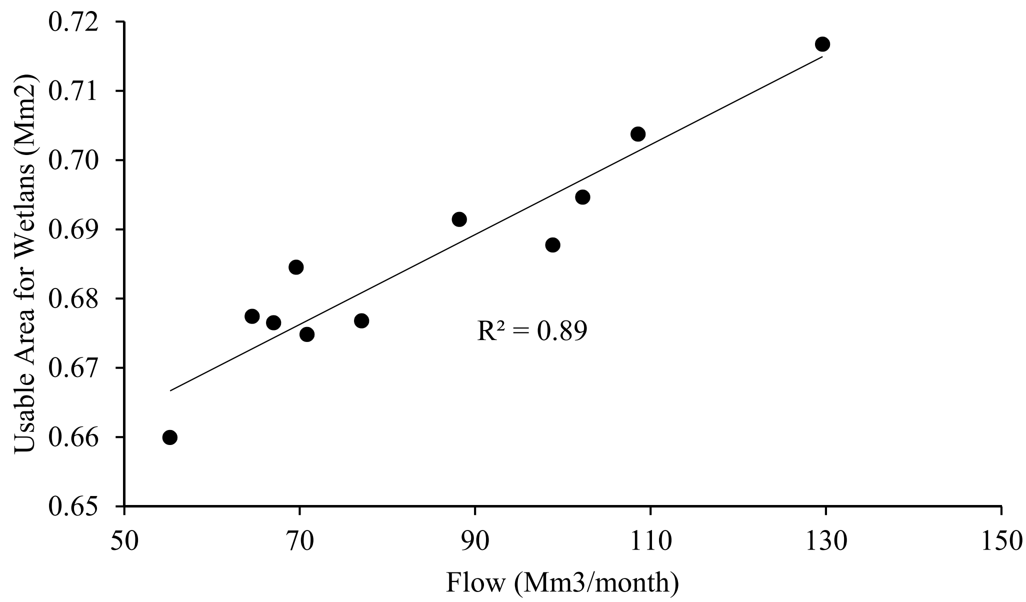

Figure 5. Example WASH wetland suitability index for February

3.3. Model Implementation

We coded the WASH model [equations 1 – 17] using the General Algebraic Modeling System software (GAMS; Hozlar, 1990) and solved the model using the non-linear global solver Branch-And-Reduce Optimization Navigator (BARON; Sahinidis, 1996). The GAMS code uses GDX (GAMS Data Exchange format) to read all input data from an MS Excel spreadsheet and pass it to the model. The 1-year implementation of the model for the lower Bear River system has approximately 27,000 variables and 5,300 equations and takes 2 hours and 15 minutes to find a global optimal solution on a Dell XPS Windows10 64-bit.

3.4. Model Scenarios

We first ran the model in simulation mode for the base case year (2003) by fixing flows on all river segments to observed gaged values. Comparing WASH habitat area under observed flows to a second scenario with flow limits relaxed shows potential habitat gains to manage water as the model recommends. We ran a third and fourth scenario with different headflows for a wetter (2005) and drier (2004) year to examine model response to changes in headflows. Additional scenarios multiplied each urban and agricultural demand in the basin by a fraction of full demand to study the tradeoff between WASH habitat area and water supply objectives. We also ran the model for 5 years (2003 to 2007) to study the effects of flow variability.

In a final scenario, we substituted habitat suitability curves for the aquatic fish species bluehead sucker *(Catostomus discobolus)* for brown trout downstream of Cutler reservoir to identify the effect of indicator species on habitat quality and area. Bluehead sucker is a nongame fish and listed as a sensitive species by state and federal agencies. Declining bluehead sucker numbers in the Utah Bonneville Basin might warrant listing bluehead sucker as a threatened or endangered species (UDNR, 2006; Webber et al., 2012). Based on the suggestion of project stakeholders, we designed a bluehead sucker suitability index using the empirical study of Anderson and Stewart (2003). These functions are Blotzmann curves that transition from 0 at a water depth of 100cm to 1 at 150cm for both adults and fry.

3.5. Model Outputs and Visualization

WASH results include recommended flows, reservoir releases, storage volumes, and temporal and spatial variations of suitable aquatic, floodplain, and impounded wetland habitat area. We used Excel, R, and ArcGIS Online to post-process and display model results in an open-access, interactive web map application (http://WASHmap.usu.edu). With the web map, users can compare modeled and simulated results, add base maps and data layers, and customize the tool. The WASHmap displays results in US Customary Units to better communicate with local stakeholders. All WASH model input data, code, and post-processing files are available at (Alafifi, 2017).

4. Results

Running the model for the case of 2003 simulated flows shows that nearly 100 thousand acres of suitable aquatic, floodplain, and wetland habitat exist in the watershed. The WASH global optimal solution shows that there is a potential to increase the overall suitable habitat area by 25 thousand acres. This overall increase is achieved with 3-, 10-, and 7- fold increases, respectively, of the suitable areas of aquatic, floodplain, and wetland habitats over 2003 modeled historical conditions in several months (Figure 6). The largest aquatic habitat increases for fish occur in May, June, and November, the largest floodplain habitat increases for plant occur in July and August on Bear River reaches above Cutler reservoir, and wetland habitat increases at the Bird Refuge occur from June to August. These suitable areas approach 53%, 3%, and 40% of the total aquatic, floodplain, and wetland habitat area in the basin.

Although wetland suitable area at the Bird Refuge increases to only 40% of the total suitable area, improvements occur during summer months and allow flows on the Bear River at Corrine to meet or exceed Bird Refuge water rights (Figure 7). Overall, the model recommended habitat area approaches 18% of the total available habitat area in the watershed if all suitability index values were at 1.

The WASH model improves suitable habitat area by increasing winter and early spring releases at Hyrum Reservoir and minimizing late spring spills at Hyrum and Porcupine reservoirs in May (Figure 8). The model increases habitat area while continuing to meet human water uses at all demand sites during winter and summer months. Additional river flow, habitat suitability, reservoir release and demand site results are available at http://WASHmap.usu.edu.

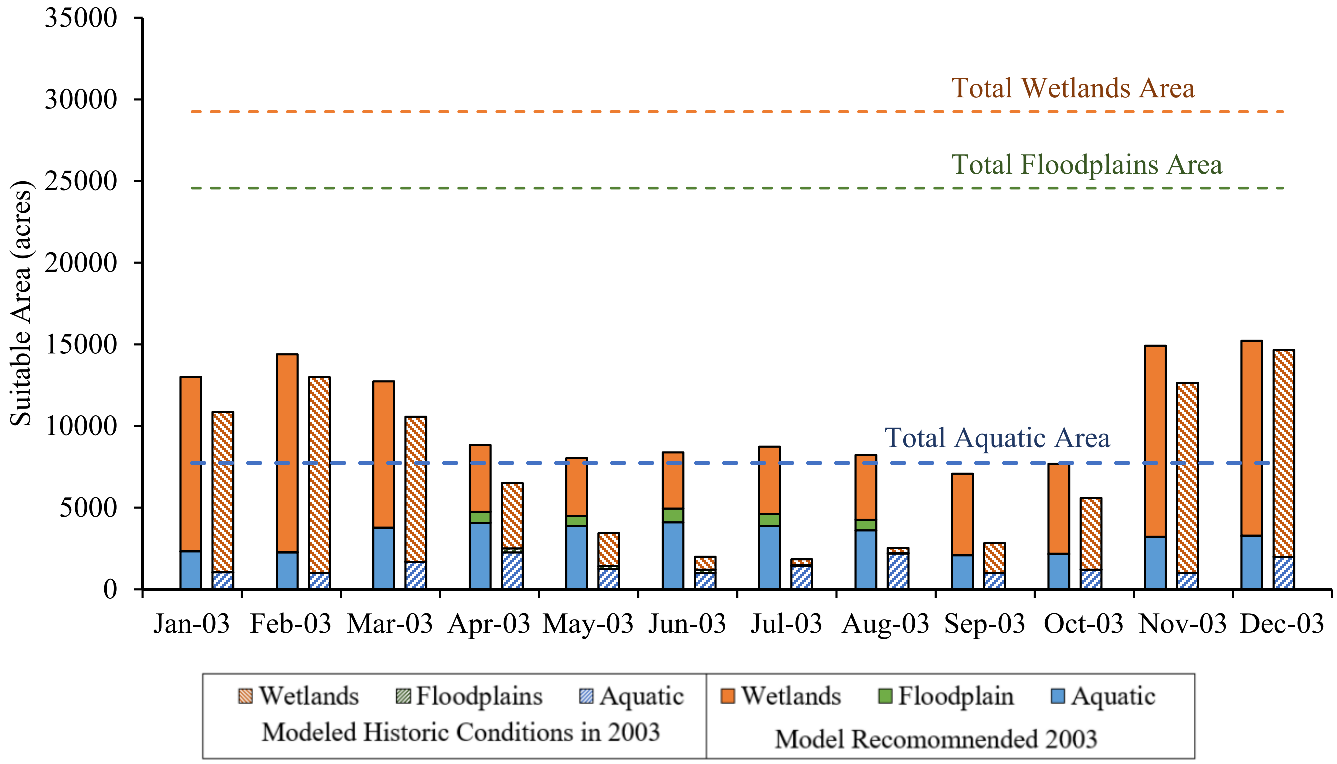

Figure 6. Monthly suitable aquatic, floodplain, and wetland habitat areas in the Bear River watershed compared to total available areas (dashed, horizontal lines)

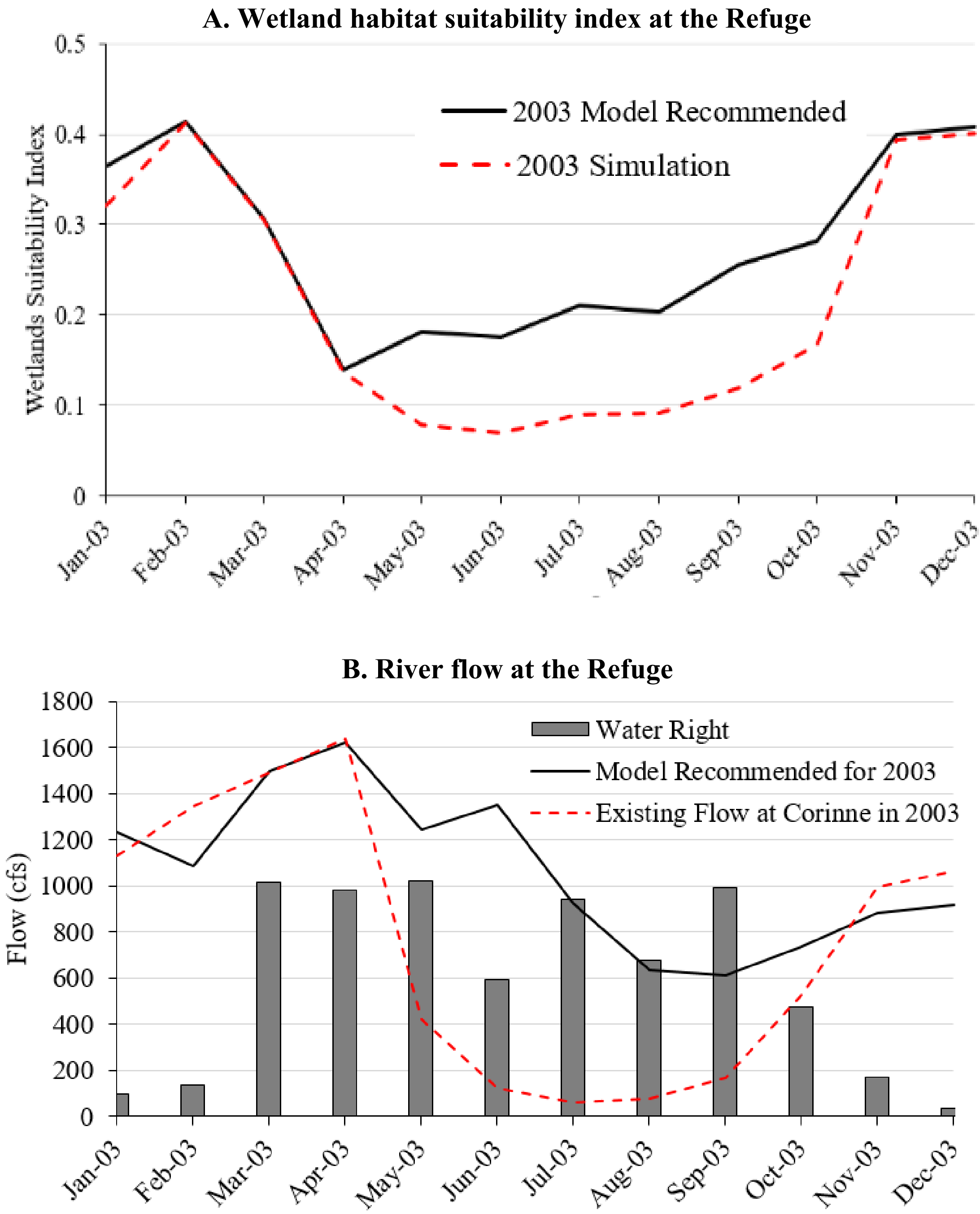

Figure 7. Model recommended improvements at the Bird Refuge in (A) wetland suitability index and (B) flows

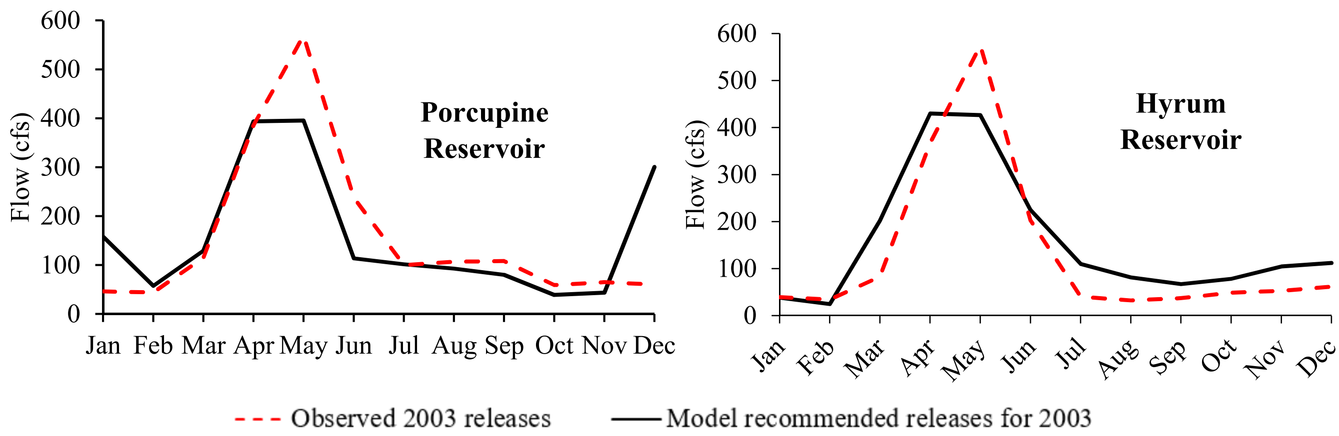

Figure 8. Comparison between model recommended and current reservoir releases for 2003 for (right) Hyrum and (left) Porcupines reservoirs

Running the model for 2005 (wet year) increased the suitable habitat area by 18 thousand acres (Figure 9, red circle) while using 2004 flows (dry year) decreased the suitable habitat area by 15 thousand acres (orange triangle). Reducing urban and agricultural demand in 10% increments increased habitat suitability area by approximately 4,000 acres per 10% reduction with most of initial increases in habitat area occurring at the Bird Refuge and in aquatic habitat on the Little Bear river. The model becomes infeasible in the 2003 base case scenario when human demands exceed 110% of existing demand.

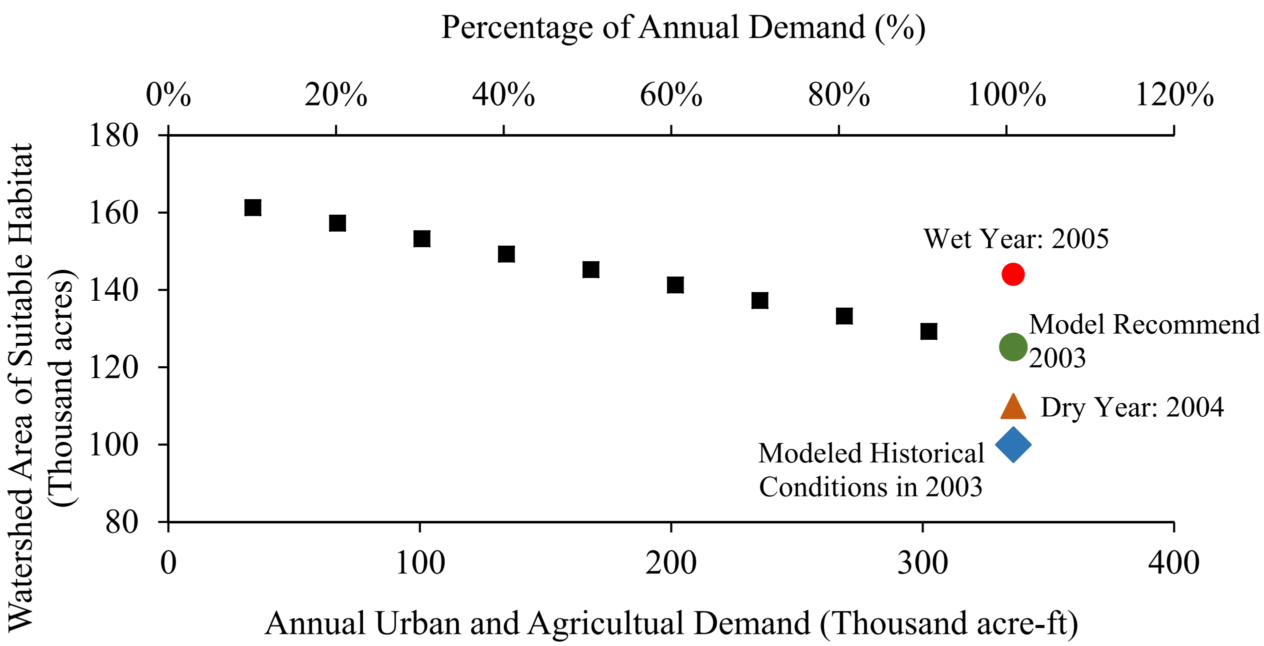

Figure 9. Tradeoff between WASH suitable area and annual demand delivery targets

Running the model for 5 years from January 2003 to September 2007 shows that the model can sustain habitat increases across annual variations in flows (Figure 10). For instance, aquatic habitat suitability dropped in 2004 but still remains higher than in comparison with modeled historic conditions case. Monthly flows and reservoir storage volumes minimize late spring spills, increase winter releases, and conform to storage and release patterns seen in the single-year run (Figure 8).

Using bluehead sucker to define aquatic habitat suitability downstream of Cutler reservoir decreased the overall WASH habitat area by 6 thousand acres from the base case with two trout species. This decrease is due to adult Suckers using deeper water depths (3.3 – 5 ft) to spawn. Also, the model has a difficult time to allocate water downstream of Cutler reservoir in summer months because upstream most water is diverted to the Bear River Canal Company that is the largest agricultural water user in the watershed.

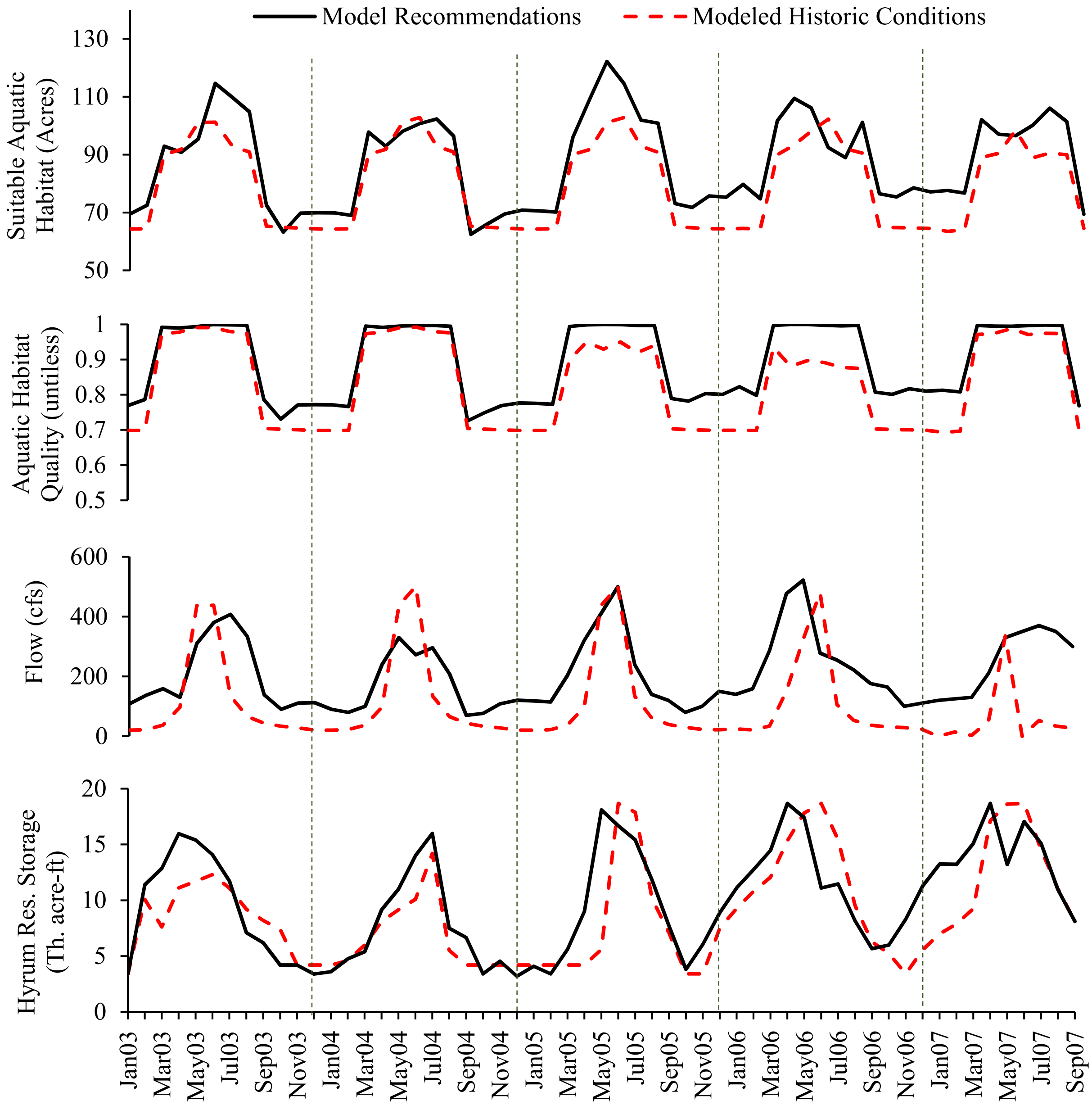

Figure 10. Comparison of suitable aquatic habitat area (acres), habitat index (unitless), flow (cfs), and reservoir releases (acre-ft) between model recommendation and modeled historical conditions for 5 years (2003 – 2007) on the Little Bear River downstream of Hyrum Reservoir and just before Cutler dam

To identify when and where water has the most ecological value, we examined the shadow values (Lagrange multipliers) associated with the water mass balance constraints at nodes with headwater flow [Eq. 7]. Shadow values report the increase in the WASH objective function value—habitat area measured in acres—per one additional flow unit (cfs) (Table 3). The largest shadow values occur on the East Fork of the Little Bear River for most months of the year. Shadow values greater than 2.5 acres/cfs are also seen on the Bear River in August, Blacksmith fork from April to October, and South Fork of the Little Bear in two months. Similarly, we examined the shadow values for the budget [Eq. 18] and found that the objective function value increases by 30 acres per additional 10,000 dollars available for planting floodplains.

Table 3. Shadow value of additional water by location and month (acres/cfs)

Shadow Values/ Month	**Jan**	**Feb**	**Mar**	**Apr**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Bear River	2.19	1.54	1.54	1.54	2.40	2.44	7.62	1.73	1.09	0.73	1.09
Cub River	1.35	0.75	0.53	2.26	0.66	2.09	0.95	0.86	1.07	0.97	0.98
Blacksmith Fork River	1.80	1.20	1.10	2.87	3.29	3.25	3.32	2.43	2.50	1.41	1.42
Little Bear River at East Fork	4.36	3.36	4.73	2.73	3.73	4.27	7.80	12.15	3.99	3.81	3.81
Little Bear River at South Fork	1.80	1.20	1.10	2.87	1.29	1.25	3.32	3.43	2.50	2.41	1.42
Malad River	0.80	0.20	0.12	0.15	0.11	0.12	0.15	0.18	0.43	0.32	0.39

5. Discussion

Formulating the WASH model objective function as a habitat area to maximize shows how to manage water and plants in the lower Bear River to increase aquatic, floodplain, and wetland habitat area for priority species in the watershed while satisfying demands of existing human users. Managing river flow and water depth in the lower Bear supports ecosystem functions of riverine species and improves habitat quality. Improving habitat quality increases the area of suitable habitat.

To increase habitat area in the lower Bear River, the model recommends to release more water from Porcupine and Hyrum reservoirs in winter months and reduce late spring spills. These changes in reservoir releases improve habitat quality and support brown trout to spawn in late fall and gravel redds to maintain their eggs until they hatch in spring. The gradual release of water from reservoirs also protects trout eggs from winter and spring flood events that could scour or kill incubated eggs and newly emerged fry (George et al., 2015). These changes in reservoir releases would likely result in small improvements in floodplain habitat area relative to aquatic habitat because several summertime diversions lower instream flows and decrease lateral connectivity to adjacent floodplains. Also, many watershed reaches border private agricultural fields and grazing lands and have narrow riparian corridors. Improving floodplain habitat area will require water and managers to set up agreements and easements with riparian landowners to return lands to floodplain functions. Changing reservoir operations, diversions, and other management actions higher up in the basin can also increase impounded wetland habitat during summer months. These results support Bird Refuge managers' recent efforts to actively communicate with upstream users and establish conservation easements. These results also suggest Bird Refuge managers should acquire upstream storage rights, forecast supply and demand, and plan for droughts.

Formulating the WASH objective function as a habitat area to maximize also shows where and when to direct scarce water, money, and planting efforts to most improve habitat. Water is scarce during summer months but WASH results suggest managers can create 2.5 to 12 acres of additional habitat per additional cfs of flow acquired during summer, fall, or winter on the East Fork of the Little Bear River or during late summer and fall months on the Blacksmith Fork and South Fork of the Little Bear. These increases contrast with increases of 30 acres per additional 10,000 dollars available to plant floodplains, and help to prioritize where to focus restoration and habitat improvement efforts.

In the scenario for bluehead sucker, the modeled aquatic habitat area for the fish decreased compared to the base case with brown trout and improving habitat quality and area will require managers to release more water below Cutler Reservoir. This flow is not currently available because of upstream diversions. Thus, future conservation efforts for bluehead sucker should include innovative water procurement plans.

The interactive WASH map facilitated work with basin stakeholders. For example, during an August 2016 model workshop, we presented key reservoir release and habitat area results (earlier versions of Figures 6 and 8) while stakeholders simultaneously explored results in real time on their phones, tablets, and laptops. Their explorations identified a problematic aspect of reservoir releases for BCT and motivated us to update aquatic suitability indexes to reflect the temperature-water depth relationship, base water depth ranges on recent fish ecology studies, and differentiate BCT and brown trout distributions.

Because WASH multiplies habitat suitability indexes by affected areas, the model structure is flexible and can be extended to include additional water quality parameters such as dissolved oxygen or biotic interactions between species (if relationships between model decision variables and the indexes can be described). Similarly, one can add other species, habitat attributes, or habitat types such as natural, oxbow, seasonal, or other wetlands in the watershed that were not included in the Lower Bear River study.

The WASH model assumes that measured and modeled water depths and channel widths are uniform along reaches that are few miles long. This assumption was made using the best available, measured data and does not capture the dynamics of stream habitat ecology. A finer spatial resolution could improve our findings. Also, including other water quality constituents besides temperature could improve estimates of habitat quality. We also assume that inundating the floodplains during seed germination and dispersal period will help riparian plants to reestablish. This neglects seedling survival which requires other biotic and abiotic conditions such as groundwater level, soil salinity, and other plant's competition for water (Bhattacharjee et al., 2008).

As a first cut effort to examine the effects of uncertainties in the empirically-established habitat suitability curves, we substituted the bluehead sucker indicator fish species for brown trout. Bluehead sucker uses deeper water to spawn and a different SI curve form. There was less flow available for environmental purpose and less habitat area for the bluehead sucker scenario. We recognize that suitability indexes (SI) carry along statistical errors that result from measurement error, spatial and temporal variability, and function form (Van der Lee et al., 2006). In ongoing research, we are evaluating and quantifying uncertainties in SI curves and their implications for water management.

The WASH model allocates water using perfect foresight of future water availability. Managers never have perfect information of future flows. However, Bear River flows are snow-melt driven and managers use snowpack measurements through the winter to forecast spring, summer, and fall water availability. Forecast reliability decreases in successive years; thus multi-year scenario results are more appropriately interpreted as the upper bound on potential habitat gains (when future flows are known perfectly).

Implementing WASH recommendations to improve habitat will also require recognizing and protecting environmental flows in the water permitting and planning process. Although Utah water law does not currently allow new appropriations of water for instream flow, more restrictive temporary or permanent transfers of existing rights to environmental users are possible (Szeptycki et al., 2015). Transfer mechanisms may include donation, lease, or purchase but must go to either the Utah Division of Wildlife Resources, the Division of Parks and Recreation, or a nonprofit fishing group such as Trout Unlimited. The State Engineer must approve all transfers (Szeptycki et al., 2015). Even if approved, the next downstream water right holder may file on and withdraw the instream flow for beneficial use.

Despite these limitations, the WASH model objective to maximize habitat area helps to identify and quantify the habitat benefits of environmental flows. The approach also helps identify locations within a watershed and times when water, money, and staff effort can most improve habitat quality and area. The approach can be extended to other regulated river systems by defining species of concern, habitat attributes, and sites, and then establishing relationships between river flow and habitat attributes of the species of concern. Quantifying results as an observable habitat area allows managers to compare model recommendations to current conditions and could motivate changes to state water law to allow more flexibility to transfer existing water rights or appropriate new water for aquatic, floodplain, wetland, or other ecological purposes.

6. Conclusions

Improving habitat in a watershed requires determining the locations, timings, and volumes to allocate water and planting efforts for priority species without harming human users. We developed a measurable, observable habitat area metric measured in acres and embedded the metric in the WASH systems model as an ecological objective to maximize. The model recommends reservoir releases, river flows, and planting to maximize habitat area subject to physical, infrastructure, and management constraints.

Application of WASH to the Lower Bear River, UT using stakeholder-verified, species- and site-specific habitat suitability curves for cutthroat trout, brown trout, cottonwood, black-necked stilt, American avocet, and tundra swan areas identified opportunities to increase aquatic, floodplain, and impounded wetland habitat area by 25 thousand acres over existing conditions. To realize this increase, release more water from Porcupine and Hyrum reservoirs in winter months and reduce late spring spills. Further, focus water transfers or development efforts in the East Fork of the Little Bear River during Summer, Fall, and Winter months to see the largest increases in habitat area per cfs of new flow. Other scenarios show WASH results are sensitive to hydrologic conditions, the length of the simulation period, and consideration of additional species. The WASH web map application provides managers direct access to results, helped us validate results, and motivated further model development to make scenarios and results more relevant to managers. Overall, developing and embedding a measurable, observable habitat area metric in a systems model as an ecological objective to maximize allowed us compare habitats across watershed sites, identify sites and times where managers can apply scarce water, money, and planting efforts to most improve habitat quality and area, involve stakeholders, and adapt the method to other basins, sites, habitat types, and species.

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Appendix A: Lower Bear River Network

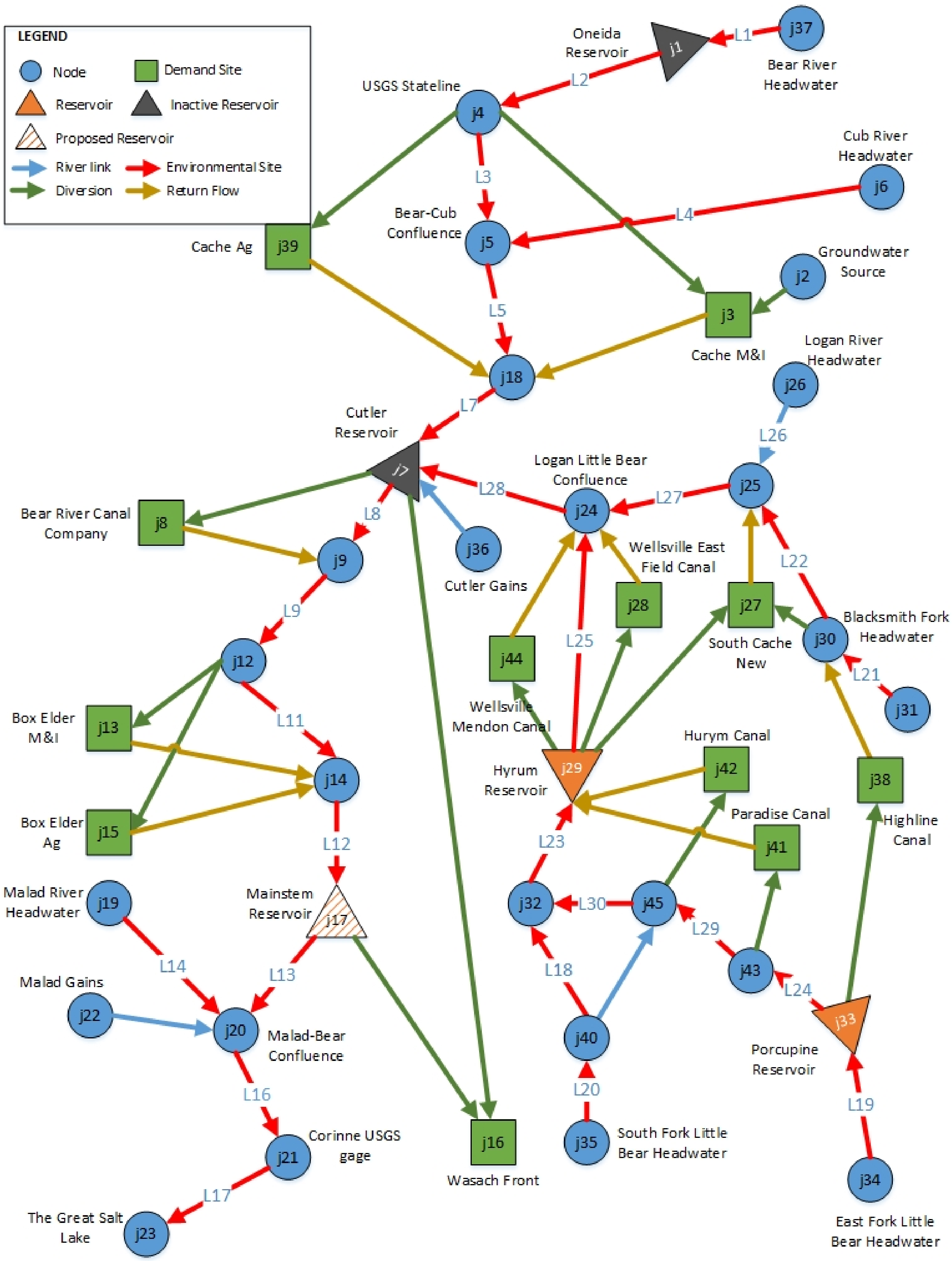

Figure 1. Lower Bear River network represented as a group of nodes and links