CEE 6410 Project: 3. Model Formulation

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Date: 10/12/2020

**1. Project description**

My objective is to develop a dual-objective optimization model for the Bear River watershed that identifies barriers to remove that maximize connected quality-weighted aquatic habitat and minimize water scarcity. Aquatic habitat will be measured using monthly average streamflow, channel gradient, and stream temperature as indicators of habitat suitability for two native fish species of management concern; Bonneville Cutthroat Trout (*Oncorhynchus clarki utah*) and Bluehead Sucker (*Catostomus discobolus*). The stream network will be derived from the National Stream Internet, and barriers identified from publicly-available sources including the National Inventory of Dams, the National Bridge Inventory, state dam and transportation datasets, and intersections between the stream network and transportation networks. Longitudinal habitat connectivity will be calculated using the dendritic connectivity index (DCI, Cote *et al.*, 2009), and with barrier passage ratings assigned from generalized type-based guidelines (Bourne *et al.*, 2011; Kemp and O’Hanley, 2010; Neeson *et al.*, 2015a; Poplar-Jeffers *et al.*, 2009; Warren and Pardew, 2004). Water scarcity costs will be calculated using economic penalty functions, and budget scenarios will constrain money available to remove barriers. This work will identify promising dam removals to improve aquatic habitat connectivity in the Bear River watershed, and expand barrier removal optimization methods by applying existing formulations in different systems and using different measurements of connectivity.

**2. Literature review**

The Bear River supports ecological, agricultural, municipal, and industrial water demands as it travels across Utah, Wyoming, and Idaho, until arriving as the largest tributary to Utah’s Great Salt Lake. The Bear River has undergone extensive alteration to meet human water needs, and current plans call for further developmet in the Bear River watershed (UDWRe, 2019). Further development poses challenges for two native fish of management concern; Bonneville Cutthroat Trout (*Oncorhynchus clarki utah*) and Bluehead Sucker (*Catostomus discobolus*). Both Bonneville Cutthroat Trout and Bluehead Sucker are threatened by habitat degradation and population isolation cause by dams, diversions, and transportation infrastructure (Schrank and Rahel, 2004; Webber *et al.*, 2012). Identification of opportunities to remove existing instream barrier can provide management actions to protect these vulnerable native fish without compromising human water development.

Instream barriers alter natural stream conditions (O’Hanley, 2011), fragment aquatic habitat (King *et al.*, 2017), and limit the distribution, abundance, and persistence of native freshwater fishes (Bourne *et al.*, 2011). Barriers also provide human benefits such as water storage, hydropower, flood control, and transportation. Optimization models that include both human and ecological objectives can identify paths to protect and restore habitat connectivity while maintaining human water demands (Null *et al.*, 2014).

Previous approaches have included aquatic habitat and economic water supply objectives in optimization models, but often rely on simplistic, ecologically irrelevant habitat models and only consider large dams for removal (Kuby *et al.*, 2005; Neeson *et al.*, 2015b; Null *et al.*, 2014). Alafifi and Rosenberg (2020) used hydrologic and vegetative indices to model aquatic habitat suitability for a systems model of the Lower Bear River watershed, but the model was designed to allocate water, financial resources, and revegetation efforts instead of barrier removal. Barrier removal optimization models have been developed, but are often limited by narrow assessment criteria that ignore biological complexity and the assumption of barrier independence that ignores the cumulative effects of spatially interconnected structures (Kemp and O’Hanley, 2010). Other barrier removal optimization models include species-specific and high-resolution input data that are difficult to transfer and replicate in different systems (O’Hanley *et al.*, 2013; Zheng and Hobbs, 2013).

Kraft *et al.* (2019) developed a dual-objective optimization model for identifying barrier removals that maximizes aquatic habitat connectivity and minimizes water scarcity. Kraft *et al.*'s approach uses generalized environmental and economic metrics that make it feasible to transfer between systems, species, and formulations. My work will build on Kraft *et al.*'s approach in three ways. First, I will test the transferability of this approach by applying Kraft *et al.*'s formulation to the Bear River watershed, a much larger and more agriculture-dominated system than it’s original application in Utah’s Weber River. Second, I will test the flexibility of the model to incorporate multiple fish species by assessing differences between barrier removal benefitting Bonneville Cutthroat Trout and Bluehead Sucker. Lastly, I will test the adaptability of the model formulation by replacing the original formulation’s connectivity index, the integral index of connectivity (Kraft *et al.*, 2019; Pascual-Hortal and Saura, 2006), with the increasingly widespread dendritic connectivity index (Cote *et al.*, 2009). My results will help to provide both a validation of Kraft *et al.*'s approach, as well as providing an analysis of how the formulation can be adapted to account for different species, systems, and environmental metric formulations.

**3. Model formulation**

*3.1 Decision variables*

Decision variables include the decision to remove individual barriers and reconnect habitat between select stream reaches. To improve aquatic habitat connectivity, managers can make a binary decision remove barrier *k* from the stream network (*Bk*). Habitat is reconnected between reaches *i* and *j* by removing all intermediary barriers (CRij), which is determined by individual barrier removal decisions (*Bk*). When objectives are combined into a single function, managers can also assign weight values to prioritize specific objectives (*w*).

*3.2 Objective function*

This linear optimization model maximizes quality-weighted aquatic habitat (km/month) and minimizes water scarcity costs for anthropogenic water uses (US$/month). The model is calculated monthly, and quality-weighted stream lengths vary with monthly instream conditions. The first objective maximizes connected, quality-weighted habitat between reaches *i* and *j* (Equation 1)

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| --- | --- | --- |
|  |  | (1) |

where *l* is the quality-weighted stream length (km) of reaches *i* and *j* in a given month, *L* is the total stream length of the stream network (km), *cij* is the unitless cumulative barrier passability between reaches *i* and *j*, and *CRij* is the binary decision to reconnect reaches *i* and *j* by removing all intermediary barriers. Zhabitat measures the degree of habitat connectivity at the watershed scale ranging from fully fragmented (0) to fully connected (1). If there are *M* barriers between reaches *i* and *j*, then barrier passability is calculated as the product of all intermediary upstream and downstream barrier passabilities (Equation 2)

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| --- | --- | --- |
|  |  | (2) |

where and are the unitless upstream and downstream passabilities of the *mth* barrier respectively. A passability of 0 indicates a completely impassable barrier, while a passability of 1 indicates a completely passable barrier.

The second objective function minimizes water scarcity costs resulting from lost water deliveries to users when a barrier is removed (Equation 3)

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| --- | --- | --- |
|  |  | (3) |

where *Ck* is the water scarcity cost (US$/month) from removing barrier *k* and *Bk* is the binary decision to remove barrier *k* from the stream network.

*3.3 Aquatic habitat*

Monthly discharge, water temperature, and channel gradient are intersected for each stream reach in each month to classify habitat suitability (Equation 4)

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| --- | --- | --- |
|  |  | (4) |

where *Qi* is the monthly percentage of the mean annual discharge (%), *Ti* is the reach-average water temperature (**°**C), and *Gi* is the channel gradient in reach *i* in a given month. Each habitat metric is classified as either excellent (1.0), satisfactory (0.5), or poor (0.1), and *Hql* can be any value between 1 and 0. The monthly quality-weighted habitat of each reach in a given month is equal to the product of the monthly habitat suitability (*Hqli*) and the longitudinal length (*Li*) in kilometers (Equation 5).

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| --- | --- | --- |
|  |  | (5) |

The two objective functions can be combined into a single objective optimization problem using the weighted sum method (Equation 6).

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| --- | --- | --- |
|  |  | (6) |

The quality-weighted habitat objective, Zhabitat, ranges between 0 and 1, and the water scarcity losses are normalized between 0 and 1. The weight value (*w*) allows managers to assign priority to one objective or the other, and ranges between 0 and 1.

*3.4 Constraints*

Model constraints represent physical, habitat, and economic bounds that restrict the objective and habitat suitability functions.

**a. Reconnected reaches**. A reconnected reach is defined as existing only when all barriers between reaches *i* and *j* are removed (Equation 7). The parameter *Inti,j,k* is a binary parameter that indicates barrier *k* occurs between reaches *i* and *j*.

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| --- | --- | --- |
|  |  | (7) |

**b. Barrier removal decision.** Barrier removals are binary decisions and may only be fully removed or not removed for all reaches (Equation 8).

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| --- | --- | --- |
|  |  | (8) |

**c. Reach reconnection decision.** Reconnecting reaches are binary decisions and may only be fully reconnected or not reconnected for all reaches (Equation 9).

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| --- | --- | --- |
|  |  | (9) |

**d. Removal budget.** Total cost of all barrier removals must be less than or equal to the barrier removal budget (Equation 10). *TC* is the barrier removal budget (US$).

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| --- | --- | --- |
|  |  | (10) |

**5. Progress Report**

*5.1 Update and major findings*

Work has primarily focused on data acquisition, model exploration, and model testing. I developed a stream network from National Stream Internet (NSI) flowlines, attributed flowlines with gradient, monthly streamflow, monthly, stream temperature, and monthly habitat suitability ratings for each species. Barrier data was acquired from multiple publicly-available sources including the US Army Corps of Engineers National Inventory of Dams, the Federal Highways Administration’s National Bridge Inventory, and state agency dam and transportation datasets. Barriers were assigned type-based passability ratings between 0 (completely impassable) and 1 (completely passable).

Kraft *et al.*'s (2019) was accessed through GitHub (<https://github.com/MaggiK/Optimizing-Stream-Barrier-Removal>) and CUAHSI HydroShare (<https://www.hydroshare.org/resource/fa37f35610c34a278042d7fc93e8c47f/>) repositories. Files include GAMS code detailing for model execution, input data to simulate the Weber River study, R code for combining large file-size input upstream path datasets, and documentation for model terminology and workflow.

I tested two runs using input data provided in the GitHub repository; a test loop using only one scenario and the full model which loops across all scenarios. The full model executed in approximately 6 hours and produced six output summaries in addition to the list file. Outputs included *results* (quality-weighted habitat for each scenario), *barriers removed* (decisions for which barriers are to be removed), *spent* (amount spent on barrier removal in each scenario), *reaches* (reaches reconnected in each scenario), *economic loss* (economic loss in dollars resulting from barrier removal), and *quality length* (quality-weighted habitat). Model execution is correct, but initial result interpretation indicates the repository code may not loop across all scenarios, but a subset.

*5.2 Anticipated challenges*

Three primary challenges remain in the completion in this work. The first is interpreting the model outputs. The model design calls for looping over multiple months, budget scenarios, and weighting scenarios for objective functions, and writes outputs to multiple files. Correct interpretation and understanding of model results from the Weber River watershed analysis (Kraft *et al.*, 2019) is needed before the model is applied to the Bear River to confirm correct model function.

The second is producing input data needed to match the input format of the GAMS code. Neither the GitHub nor HydroShare repositories included data for how to reproduce the input data; specifically stream network connection matrices. I have contacted the lead author, who has provided me with a rough idea of the workflow. However, uncertainty remains about whether the workflow will result in usable input data that will allow the model to execute for the Bear River watershed.

The third and final challenge remains correct execution of the model in the Bear River and interpretation of model results. Once input data is developed, model testing will be needed to ensure successful execution. Model results will need to be reviewed for error, and expert opinion will be needed to interpret the reality of model solutions.

*5.3 Plan for project completion*

**1. Interpret model testing results** – This task involves interpreting the test-run model results and comparing them to results from Kraft *et al.* (2019). Confirming results will indicate correct model function, and support interpretation of future Bear River model results.

**2. Develop input data for Bear River model** – I’ve corresponded with Maggi Kraft, who provided some information about how to repeat the process. I’ll review and test the recommended methods to generate this input data. Failing this, a simplified stream and barrier network (i.e. ‘dummy’ data) could be developed to simulate application to the Bear River watershed.

**3. Test Bear River barrier removal optimization model** – This model should only require replicating and appropriate input dataset for the Bear River. The final step will be to use the input data developed in Step 2, then run the model for the Bear River. Results will be compared to Kraft *et al.*'s (2019) results for the Weber River to assess how decision making varies between the two systems.

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