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Beaver Dam Analog Prioritization

A Spatially Explicit Cost-Effectiveness Model

by

BA Daniel Walsh
s1098800

Supervisor:
Phd. Gudrun Wallentin

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Contents

Abstract

Beaver dams provide many ecosystem services in the semi-arid regions of western North America. Modification of channel morphology and creation of wetland complexes through the creation of beaver dams can increase groundwater infiltration, improve riparian habitat density and diversity, attenuate flood severity, and protect streams and ecosystems that depend on them from drought. Unfortunately, the near extirpation of North America beaver in the 18th and 19th century has prevented these benefits from being realized in many places they historically were. In recent years, Beaver Dam Analogs (BDA) have been proposed as a method for restoring degraded stream channels to a state where the introduction of beavers would be feasible. These low-tech, artificial structures, consisting of stakes driven into the stream bed with branches woven between them to emulate a real beaver dam, help the channel aggrade, reducing the prevalence of incised channels, which are inappropriate for beaver reintroduction due to increased stream power and concentrated flows. Once beavers are reintroduced, the stream system enters a new equilibrium and no longer requires action by humans to stay in this new state. In this paper, I present an integrated cost-benefit based project prioritization model referred to as the Beaver Dam Analog Prioritization (BDAP), which is designed to help land managers decide where to invest limited resources in the construction of BDAs. The model first simulates the cost and benefit of installing individual beaver dam analogs along stream reaches meeting certain beaver dam analog feasibility criteria. The cost is considered directly proportional to installation time and the benefit is proportional to the area flooded by the dam. Once each dam has been quantified in terms of costs and benefits, dams are combined into many possible dam clusters – sets of BDAs that would produce contiguous beaver habitat. The overall cost and benefit of constructing each cluster of BDAs is then computed, considering the fact that crews may be able to complete more than one BDA per day, thus reducing the travel time required to and from the site. The result is a prioritized set of BDA clusters which managers can use to determine where to install BDAs to produce the greatest benefit. The results, based on over 12,000 dams modeled across 37.2 km of stream channels with a 3 m spacing, suggest that BDA clusters consisting of lower dams (0.6 rather than 1 m) and shorter dam crest lengths tend to have higher benefit-cost ratios. In addition, in the study area, BDA clusters located in low-gradient, broad valleys tend to have the best benefit-cost performance. Finally, the impact of crew travel time on modelled cluster cost was minimal in the study area (8% of the average cost). Several potential improvements to the model are described in the future work section.

Introduction

Background on Beaver-Based Restoration

North American Beaver (*Castor canadensis*) are known to play a beneficial role in enabling healthy function in riparian ecosystems. Modification of channel morphology and creation of wetland complexes through the creation of beaver dams can increase groundwater infiltration, improve riparian habitat density and diversity, attenuate flood severity, and protect streams and the ecosystems that depend on them from drought (Kornse and Wohl, 2020, Scamardo and Wohl, 2019, Jordan and Fairfax, 2022, Wohl, 2021, Wheaton et al., 2019, Gibson and Olden, 2014). Unfortunately, the near extirpation of beavers in sub-boreal North America in the 19th century and subsequent destruction of beaver dams has disconnected many streams from their historic floodplains, leading to the loss of the benefits these dams provide (Wohl, 2021).

In recent years, acknowledgement of the scale such stream degradation and prohibitive expense of addressing it using traditional engineering approaches has led to interest in process-based stream restoration, which aims to move stream systems across tipping points into new natural equilibria with minimal application of materials and energy (Jordan and Fairfax, 2022, Wheaton et al., 2019, Pilliod et al., 2018, Nash et al., 2021). While introducing beaver may be the obvious process-based restoration technique, due to stream incision, many sites that once hosted beaver populations are not currently suitable for reintroduction. Beaver dam analogs (BDAs) - simple, human-made structures designed to replicate the benefits of beaver dams and prepare stream systems to receive beaver reintroduction in the future – are one way to restore these degraded streams (Norman et al., 2022).

Considerable attention has been given to the problem of determining where beaver introduction is likely to succeed in increasing the number of beaver dams. Initial efforts, such as those of Allen (1983), focused on developing suitability indexes based on expert assessment on the ground. This method is not suitable to generalization and must be calibrated to local geologic, climate, and ecological conditions. More recently, Macfarlane et al. (2015) developed BRAT (Beaver Restoration Assessment Tool), which uses a Fuzzy Inference System capacity model and publicly available geospatial data to estimate the density of beaver dams that a river could theoretically support. Using BRAT, Kornse and Wohl (2020) estimated the maximum carrying capacity for beaver dams in Colorado and determined that the model was most sensitive to changes in vegetation availability. Also using BRAT, Scamardo et al. (2022) concluded that Colorado streams once could have supported 2.4 million beaver dams, while modern stream systems might only support up to 1.4 million dams. Much of this decline was due to declines in vegetation types needed for the construction of dams.

The use of BDA to prepare channels for beaver reintroduction has been considered by many authors over the past two decades (Pollock et al., 2012, Pollock et al., 2014, Pollock et al., 2015, Pilliod et al., 2018, Scamardo and Wohl, 2019, Wheaton et al., 2019, Westbrook et al., 2006). According to (Pollock et al., 2015), BDAs are “channel-spanning structures that mimic or reinforce

actual beaver dams". Unlike engineered stream restoration structures, BDA are low tech structures that are typically built by hand using locally sourced materials. Best-practice techniques for building BDA are summarized in (Wheaton et al., 2019). BDA sites are typically accessed on foot from the nearest road, and work is completed by labor crews using simple equipment including chainsaws, block and tackles, and post drivers. Crews cut and sharpen locally sourced or imported wooden stakes and drive them into the stream channel. Then, additional locally sourced woody debris are cut and hauled to the dam location, where they are woven between the stakes, creating a channel-spanning structure capable of capturing sediments, aggrading incised channels, and flooding ponds upstream. Wheaton et al. note that constructing an individual BDA can take 30 minutes to "half a day", depending on the width of the structure.

Pollock et al. (2015) note that BDA provide the greatest benefit when multiple dams are installed to create a contiguous inundated area. Larger numbers of dam provide greater hydrologic impact (dissipating greater amounts of flood energy and increasing sediment deposition and floodplain connectivity, more contiguous wetland habitat, which is more suitable for future beaver-centric ecosystems because it more closely emulates natural analogs, and a greater degree of system resilience – the loss of any one dam due to a flood has less of an impact the more dams there are in the cluster. In conclusion, any attempt to prioritize BDA placement locations must put an emphasis on creating large, multi-dam structures that provide the benefits listed above.

Figure 1- A typical natural beaver dam. BDAs attempt to provide the same ecosystem services and prepare the stream for the reintroduction of beaver. Credit: (c) 2012 Tom Kelly (CC License)

Figure 2 – A beaver dam analog during high flows (Public Domain, USFWS)

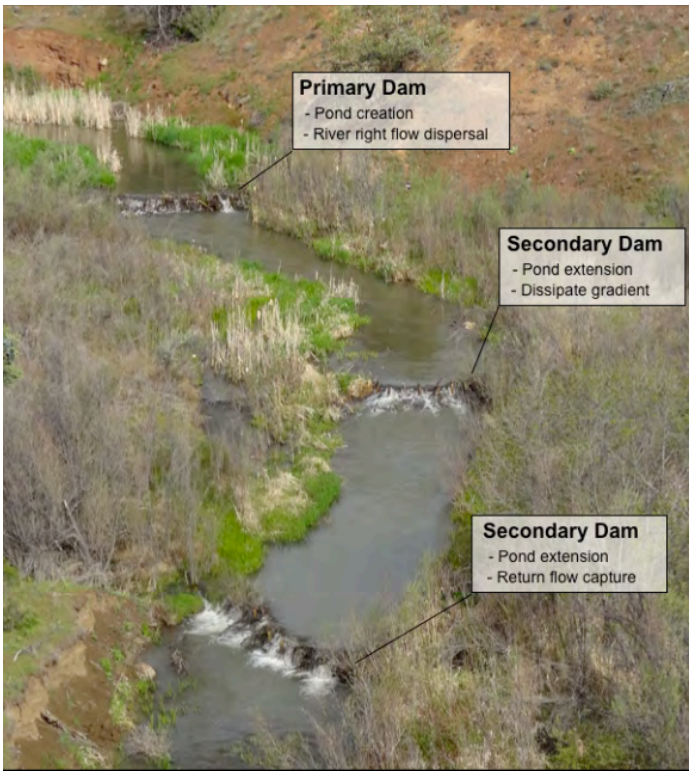

Figure 3 – A sequence of BDAs where the tailwater of one dam backs up to the base of the next. BDAP prioritizes such sequences by benefit cost ratio. (Public Domain, USFWS)

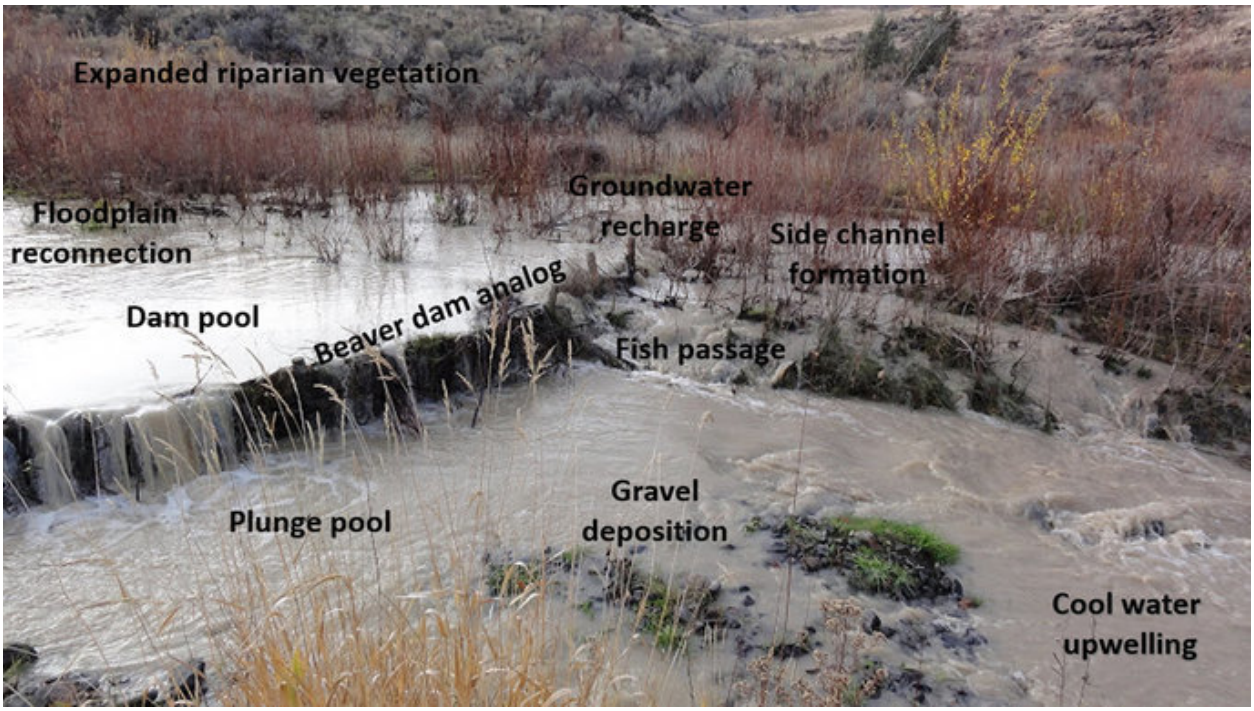

Figure 4 – Figure showing the benefits of BDA installation. The channel is reconnected to the floodplain, allowing for groundwater recharge and side channel formation. Gravel is deposited below the dam due to decreased flows, and a plunge pool and fish passage provide ecological benefits. Finally, the riparian vegetation zone grows, reducing flooding and providing critical habitat. (Public Domain, USFS).

Figure 5 – An incised channel in Idaho, USA. The stream has become disconnected from its floodplain (Public Domain, USFS).

Beaver Dam Analog Prioritization Tool

Although BRAT allows us to see which stream reaches can theoretically support beaver populations, it does not assess which reaches could benefit the most from BDA and eventual beaver reintroduction. In addition, it does not assess the suitability and cost of installing BDA.

This study aims to address these shortcomings by developing a decision support model that prioritizes stream reaches for the construction of BDA based on maximizing projected benefits and minimizing costs. The model will (1) determine the cost and benefit of installing individual BDAs along the stream network and (2) create and prioritize clusters of BDAs that can be constructed within a user-provided time budget. The model will be evaluated on a region in Colorado with diverse beaver habitat, existing BRAT results, and high-resolution DEM data.

This integrated cost-benefit based project prioritization model, referred to as the Beaver Dam Analog Prioritization (BDAP), is designed to help land managers decide where to invest limited resources in the construction of BDAs. The model first simulates the cost and benefit of installing individual beaver dam analogs along stream reaches meeting certain beaver dam analog feasibility criteria. The cost is considered directly proportional to installation time and the benefit is proportional to the area flooded by the dam. Once each dam has been quantified in terms of costs and benefits, dams are combined into many possible dam clusters – sets of BDAs that would produce contiguous beaver habitat. The overall cost and benefit of constructing each cluster of BDAs is then computed, considering the fact that crews may be able to complete more than one BDA per day, thus reducing the travel time required to and from the site. The end result is a prioritized set of BDA clusters which managers can use to determine where to install BDAs to produce the greatest benefit.

Study Area

To enable the assessment of the resulting BDA prioritization model and ensure that the model would be applicable to a wide range of landscape types, I chose a study area with a diverse range of beaver habitat, moderate human presence, and a reasonable area for the proof of concept. I decided to delineate the study area using the boundaries of HUC watersheds. Initially I planned to use HUC12, but the area was too large for processing in a reasonable time span, so I chose a sub-basing at the HUC10 scale.

The King Solomon Creek watershed (Figure 6) is an HUC10-scale watershed located in north-central Colorado. It spans latitudes from 40.8-41 degrees north and longitudes from 106.7 to 107 degrees west. The watershed is dominated by King Solomon Creek, which runs at the base of high ridges to its east and has several tributaries that dissect the hills to the southwest. The landscape is varied, and includes open meadows, aspen forests, and high elevation mixed conifer forests, as well as some areas of alpine vegetation. It is a typical high elevation watershed in Colorado in that the landscape and ecology changes drastically depending on the slope aspect, with wet north-facing slopes and semi-arid south-facing slopes. Valley bottoms range from deeply incised, steep valleys unsuitable for beaver to broad, sedimented valleys more suitable for beaver. Elevations range from 2024-3306 m.

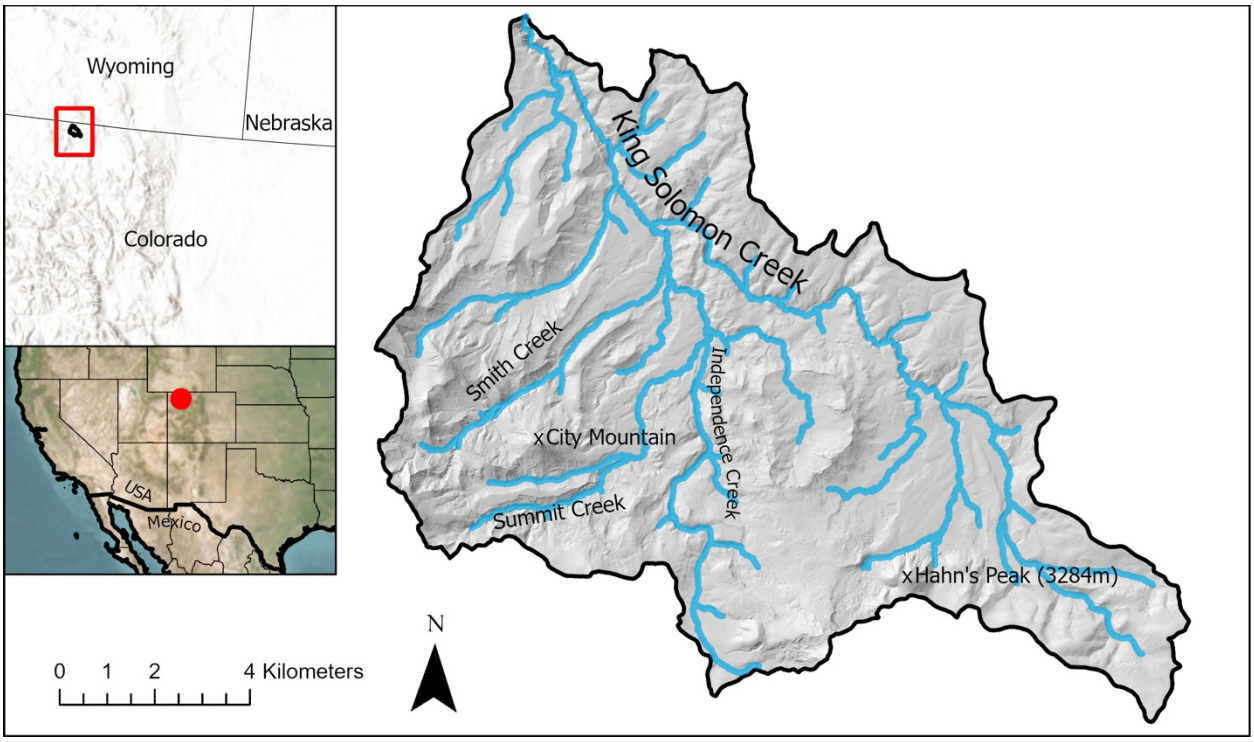

Figure 6 – King Solomon Creek watershed.

Table 1 – Characteristics of the watershed and the larger HUC10 watershed (Little Snake) that it lies within.

Study Area	Derived From	Little Snake	King Solomon Creek
Area (km^2)	Watershed	997.8	222.0
Elevation Range	DEM	2038-3356 m, range: 1317 m	2224.5-3306 m
Km of Stream Channel	DEM	997.3 km	135.9
km Of Stream Channel with "Pervasive" BRAT rating	BRAT/DEM		37.2 km

Table 2 – List of model input data sources.

Data	Source	Characteristics
DEM	USGS 1 m 3DEP DEM	1 m resolution, high coverage.
Street Maps	OSM Roads	Classified
BRAT Output Colorado	BRAT Model	Polyline features
Parcel Data	Routt County Parcels	Polygon
Watersheds	USDA HUC	Polygon

The maps in Figure 7 provide an overview of the geography of the watershed and introduce the primary databases that are used in this analysis.

Panel A shows the BRAT database produced by Macfarlane et al. (2015). This database rates stream reaches throughout Colorado by the number of beaver dams predicted to be theoretically supported by the landscape per km, as computed for each 300 m stream reach. It is used to determine which stream reaches should be included in the BCA. Blue reaches correspond to areas defined as able to support "pervasive" beaver dam densities greater than fifteen per kilometer.

Panel B shows the DEM (USGS, 2024) used for the analysis, which has a horizontal resolution of 1 m and a vertical resolution of 0.1 m. Panel B shows the road network within the watershed, as defined by Open Street Map roads with a "class" designation of 5 or greater (openstreetmap.org, 2024). This corresponds to roads accessible using high-clearance pickup trucks.

Panel D shows land ownership within the watershed (Routt County, 2024). 93% of the land is owned by the US Forest Service, with about 0.5% owned by the US Bureau of Land Management and the remaining 6.5% privately owned. BDAP does not consider land ownership, but the user might decide to limit the input dataset to certain ownership classes to meet their needs.

Panel E shows the travel time to each point on the map from the nearest road, as calculated according to the methods described in the section Cost Model: Travel Time. The greatest travel time is in the southwest, where widely spaced roads combined with steep terrain render the landscape relatively inaccessible on foot. Finally, Panel F shows the travel rate (time to traverse each pixel) used to produce the travel time map.

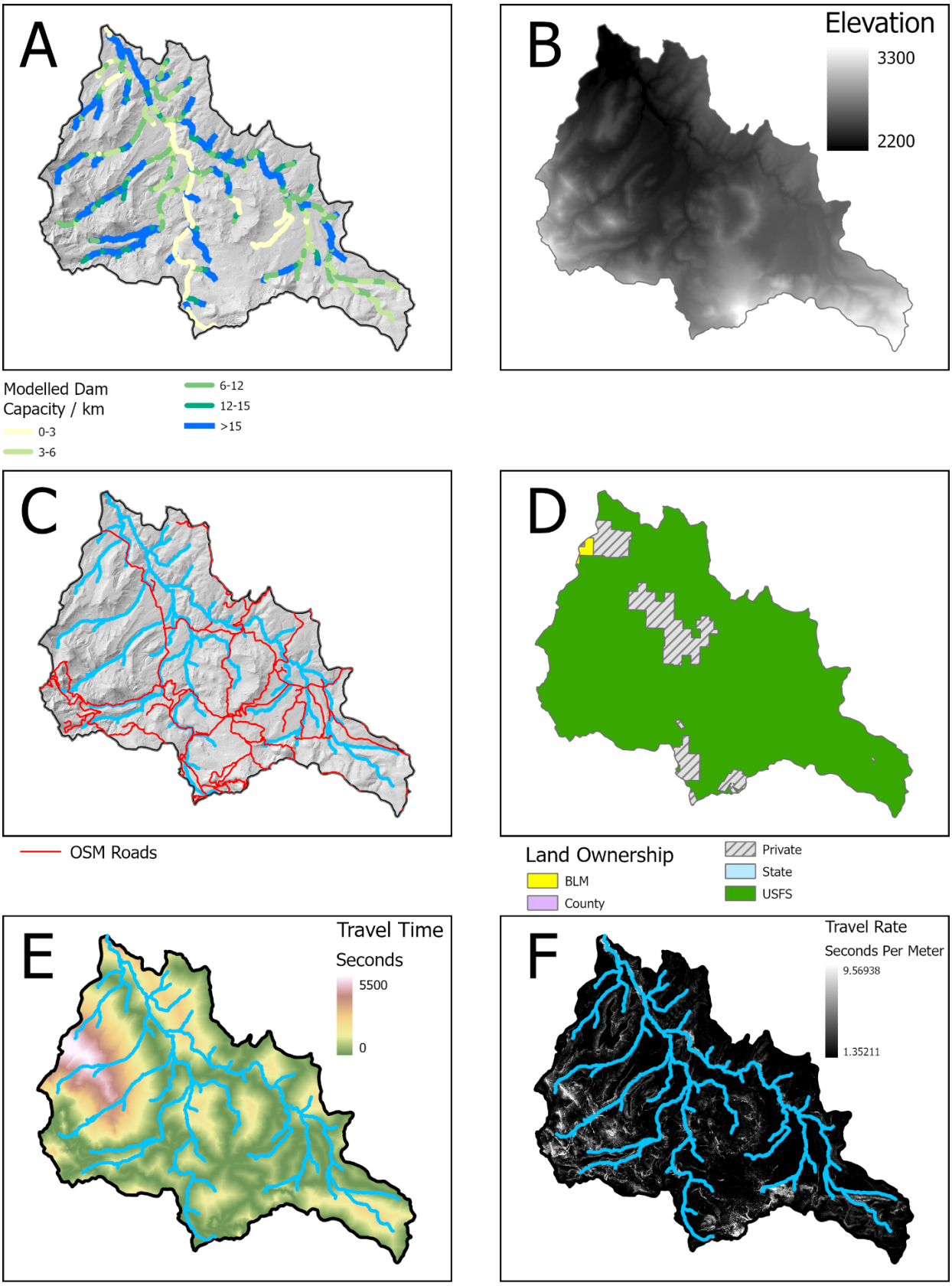

Figure 7 – Overview of the King Solomon Creek study area. See text throughout for descriptions of each map panel.

Methods

Spatial Cost Effectiveness Analysis: Background

BDAP implements a benefit-cost model to assist the user in identifying the most promising BDA complexes. The cost-benefit model has a history dating back at least to 1844, when engineer Jules Dupuis developed a model to justify the construction of a bridge. The benefit of the bridge was in that case measured by the utility of bridge users (as quantified by how much they would be willing to pay to construct the bridge), and the cost was calculated from the actual costs of building the structure (Abelson, 2022). Since that time, cost-benefit analysis has become a regular, and required, part of decision-making on behalf of government agencies and those they regulate (Sunstein, 2005).

More recently, cost-effectiveness analysis was developed to allow for effective decision-making in situations where costs and benefits are non-monetary. Cost-effectiveness analysis ranks potential options by comparing the ratio of benefits to costs for each option (Zhou et al., 2009, Robinson, 1993, Moran et al., 2010). The ratio of costs to benefits, rather than the absolute costs and benefits, is used to prioritize and compare alternative options.

Spatial applications of cost-effectiveness analysis have been implemented for a variety of fields within natural resources, including reforestation (Wainaina et al., 2020), wildfire risk reduction (Jones et al., 2022), and river restoration (Logar et al., 2019).

In the case of BDAP, costs are quantified in terms of the time required to construct a given cluster of BDAs. Since materials are collected from the local environment, the only cost of installing a BDA cluster is the cost of hiring laborers, which is assumed to be directly proportional to the time they are hired for. Changes in labor rates will multiply each cluster's benefit cost ratio (BCR) by the same constant. Since we are concerned with ranking possible BDA clusters, and not with defining the absolute benefit they provide, it is more straightforward to use time as a proxy for cost.

The benefit of each BDA cluster should be proportional to the environmental benefit provided. For BDAP, the benefit is assumed to be directly proportional to the inundated area, though in the future the model could be made more sophisticated by, for example, considering how degraded the stream channel is currently, as in Fryirs and Brierley (2013), since more degraded reaches may benefit more from the installation of BDAs (Pollock et al., 2014).

The implementation of cost-effectiveness analysis in BDAP consists of (1) a pre-processing model that prepares a digital representation of the stream network on which analysis is completed, (2) a cost model that quantifies the cost of building each dam, (3) a benefit model which quantifies the benefits of each dam, and (4) a dam clustering model which calculates the overall costs and benefits of clusters of BDAs and ranks them using the outputs of the cost and benefit models. The result is a ranked set of non-overlapping BDA clusters, each with an associated benefit and cost, which can be used to inform decision-making on where BDA clusters should be installed. The final

output creates an idealized ranking; in reality, decision-makers may be unable to pursue the top-ranked choice due to external factors such as the presence of private property or consideration of other factors not integrated into BDAP and thus may eliminate some complexes from consideration.

Each of the four components of the model introduced above is described in detail in the following sections.

Preprocessing: Hydrologic Stream Network Creation and Alignment with BRAT Features

The preprocessing step allows us to integrate the results of BRAT analysis (discussed above) with a stream network that conforms to flow paths on the more detailed 1-m dem used for analysis herein. I chose to use a 1-m DEM produced by the USGSs 3DEP program (USGS, 2024), which derives elevation measurements using LIDAR, photogrammetry, and radar to produce a continuous raster coverage of the United States. The 1-m resolution increased processing time over lower-resolution datasets but was required because of the small scale on which analysis must occur to accurately simulate dam width and pond inundation.

Stream Network Creation and Alignment with BRAT

To make the model implementation more efficient, I chose to consider segments of streams for BDA installation where the BRAT model suggests high habitat suitability (potential beaver dam density exceeding 15 dams/km). The rationale for this is described in the following section. Panel A in Figure 7 shows the BRAT rating for streams within the watershed. Streams are rated by the number of dams that are determined by the model to be able to support per kilometer; streams are divided into 300 m segments for assessment.

Unfortunately, the BRAT model output was derived for a stream network derived from traditional maps rather than one derived from a DEM, meaning that the BRAT result streams do not always follow a hydrologically realistic path on the DEM. This poses a problem because a DEM analysis will be used to simulate beaver dams in the benefit part of the BCA. Thus, I needed to (1) create a hydrologically correct stream network and (2) align the BRAT segments with hydrologically correct segments derived from the dem to filter the hydrologically correct segments by habitat suitability.

The stream network was obtained via a classic DEM analysis (Quinn et al., 2006, Chen et al., 2024, O'Callaghan and Mark, 1984). First, flow directions for each cell were calculated from a DEM. Next, flow accumulation tools were used to determine the number of cells flowing into each cell. Finally, the results are classified with all cells with accumulation values over a give threshold classified as a stream and converted into a polyline. The main decision I needed to make was to determine the minimum number of contributing cells to use when identifying stream channels. I considered calculating the number of cells required to reach a minimum discharge suitable to beaver dams given the average precipitation in the region. However, I realized that the BRAT model uses a more sophisticated methodology for determining discharge, and that the presence or absence of the

proper discharge would already be reflected in the output of BRAT (the predicted number of dams that could be supported per km of stream reach).

I used the following set of steps (Figure 8) to transfer data from the BRAT segments (the number of dams predicted to be supported per km) to equivalent segments in a topographically correct stream network derived from the DEM:

1. Split DEM derived stream segments into 300 m sections with unique IDs.
2. Split all DEM derived stream segments into many straight-line segments, retaining the origin stream segment ID.
3. Identify the BRAT segment closest to each straight-line segment.
4. Join the BRAT beaver dam density value from the BRAT segment to the matching straight-line segment.
5. Calculate the weighted average of dam density values (weighted by straight line length of each straight component relative to segment length) for each segment ID.

This method allowed me to transfer density values from the BRAT segments to the DEM-derived stream segments while adjusting for differences in location and segment length. There may be cases where the nearest stream segment is not hydrologically connected to the DEM-derived segment, this issue could be addressed in future versions of the tool by using flow distance rather than straight line distance – in this case, the computational resources required would be excessive for a pilot model and visual inspection suggested that the transfer of values was, in general, reasonable.

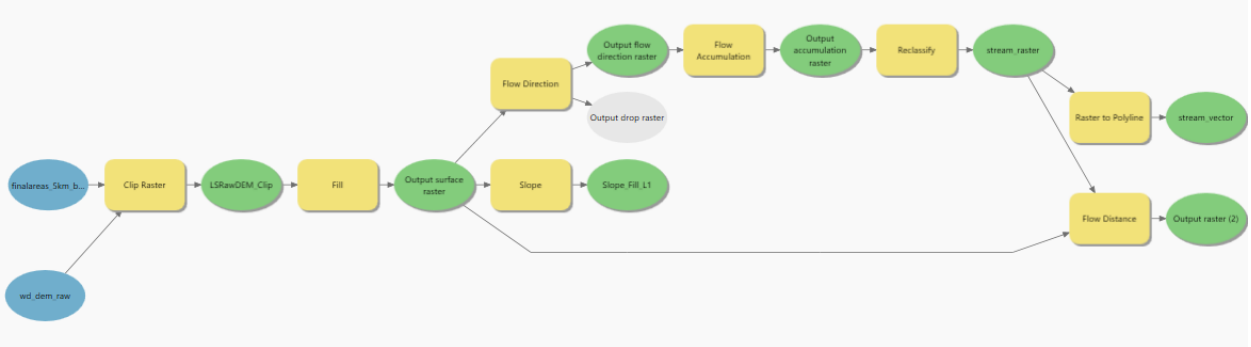

Figure 8 - Method for deriving stream flow paths from the 1 m DEM.

Figure 9 - Example of misalignment between DEM derived, hydrologically correct segments (blue) and segments containing data from BRAT (red). After completing the steps outlined above, the PotentialDamPerKm values from BRAT were transferred to the closest point in the DEM-derived dataset and then summarized for the 300 m segments that were generated for streams in the DEM-derived dataset

Filtering Stream Segments

The aligned streams and associated 1-m DEMs allow us to assign beaver dam densities from BRAT to a hydrologically correct stream network divided into 300 m reaches. However, not all reaches of the stream network are appropriate for beaver reintroduction or BRAT. Although all reaches could theoretically be analyzed, to reduce computational demands for the proof-of-concept, and also to ensure stream reaches are actually appropriate for the reintroduction of beaver and BDA, I chose to only assess reaches within the "pervasive" beaver dam density described by Macfarlane et al. (2015). "Pervasive" describes reaches with >15 dams/kilometer. Approximately 36 km of streams within the King Solomon Creek study area meet this criterion. The use of 300-meter stream segments allowed for continuous stream segments where the average met the criterion, allowing for continuous simulation and clustering of BDAs.

The resulting filtered stream segments represent all the possible locations that will be prioritized for BDA cluster creation by BDAP and are shown in dark blue in panel A of Figure 7.

Cost Model:

BDAP uses a time-based cost model as input to the benefit cost analysis. For each potential BDA installation point, the number of person-hours required to install a dam at that point and the time required to reach that point from the nearest road, as derived fromopenstreetmap.org (2024), are computed. These times calculated for individual dams are then used to determine overall benefits and costs for each dam cluster under consideration.

The time required for each dam is:

$$T_s = Tt + Ti \qquad \text{(Equation 1)}$$

where Tt is travel time and Ti is installation time.

Cost Model: Travel Time

In BDAP, travel time required for the completion of each dam cluster is calculated. As described below, this travel time is based on the average of the travel times to each dam in the cluster. Thus, the model requires us to know the time it would take a worker to reach each dam in the dataset.

Numerous models have been proposed and calibrated for estimating human travel time across landscapes (Pingel, 2010, Minetti et al., 2002, Wang et al., 2013). For BDAP, travel time is calculated using a modified form of the model proposed by Irmischer and Clarke (2017):

$$S = 0.95 * \left(0.11 + 0.67 * e^{\frac{-(slope+2)^2}{2*30^2}}\right) \qquad \text{(Equation 2)}$$

where

$$Slope = \frac{\Delta\, elevation}{\Delta\, distance} * 100$$

This model is based on the movements of real people who were not following a marked path and thus had to navigate like BDA crews will need to.

To implement the travel-time model, I calculated the time required to reach each point in the study area from the nearest road. In ArcGIS Pro, this can be accomplished using the cost accumulation tool. The first step is to create a cost surface, which describes the amount of time required to traverse each grid cell in a raster. The cost surface was calculated by first calculating a % slope raster with a resolution of 1 m. That raster was then used as the *slope* variable in Irmisher's equation, which was then calculated for each grid cell in the study area using raster calculator with the following expression:

```
expression='1/(0.95*(0.11+0.67*2.718**(-((Raster("wd_dem_pct_slope.tif")+2)**2)/1800)))'
```

The expression was inverted because Irmisher's equation provides meters/second, but in this case, we wanted seconds per meter. The total time to cross each 1 m cell was calculated (Figure 7, panel F).

To reduce computational intensity, I calculated the time required to reach each grid cell in the study area from the nearest road on a grid with a resolution of 100 m (using the distance accumulation tool). I chose 100 m because it was a tradeoff between decreasing computation time and improving the accuracy – as each pixel becomes larger the standard deviation of the actual slope from the overall interpolated slope increases. Since 100 m is also on the same scale as a typical BDA cluster, decreasing size beyond that was deemed unnecessary.

Using Python scripting, I ran the cost accumulation tool using the navigable roads dataset as the source feature. This produces a raster showing the time required to reach each cell on the map from the nearest road. I then used "extract values to points" to extract the time-to-reach value (in seconds) to each potential BDA. The results can be seen in Figure 7 (panel D).

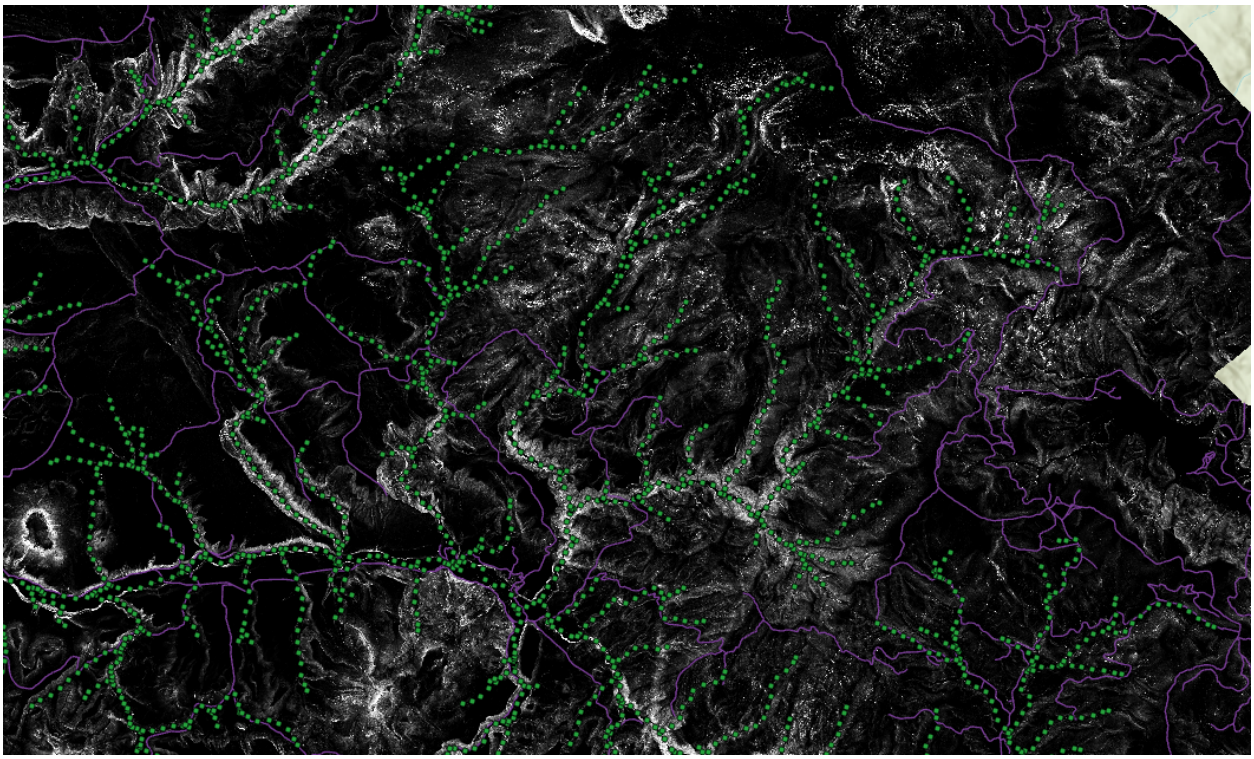

Figure 10 – Portion of study area with Irmischer's equation calculated from the 1 m DEM.

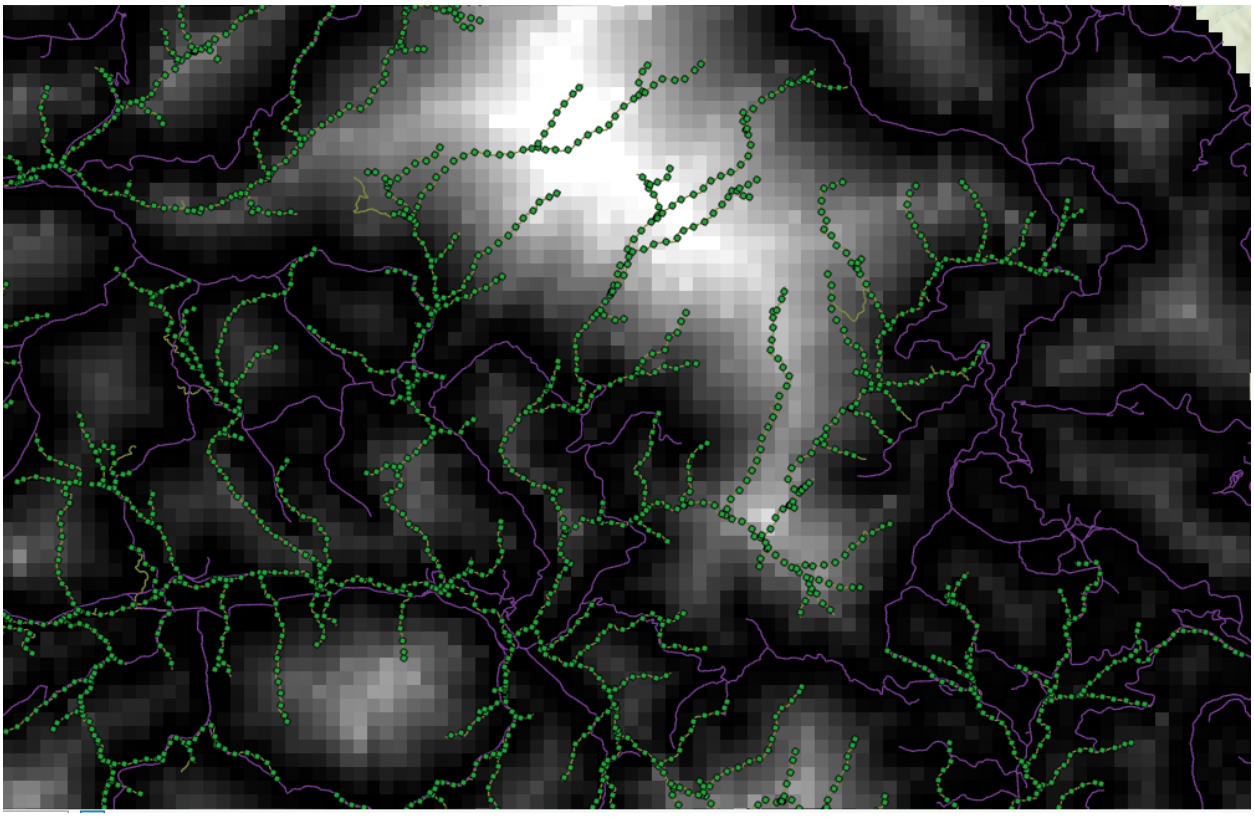

Figure 11 – Travel time raster with 100 m cells. The color represents the amount of time to reach a given point from the nearest vehicular road (shown in purple). The point it takes longest to reach has the lightest white color, and the fastest points to reach have a dark color. In the area shown above, the time to reach a pixel range from 0 s to 9,950 s (0-2.76 hours) and depends on both distance from the road and the cumulative slowing effect of terrain slope. The green points are representative dam locations which are used to extract the travel time values.

The results of travel time modelling are shown in Figure 7, panels E and F. Panel F shows the number of seconds estimated to be required to traverse one 1mx1m pixel in the image. The flattest cells were estimated to take only 1.3 seconds to cross, while the steepest were predicted to require almost 10 seconds (the equation likely underestimates traversal times on very steep segments which might in fact be practically impassible. The cost accumulation tool was used to find the least cost path from each beaver dam location to the nearest road. The results (Panel E) show that every point on the map can be reached in between 0 and 5500 seconds (approximately 90 minutes), depending on terrain and distance from a road.

Cost Model: Dam Construction Time

Determining Number and Size of Required Dams

Dam width is equal to the width of the channel/valley cross section containing points that are less than vertical distance *h* (dam height) above the lowest point of the channel (elevation of which is denoted *e*). Since transects may intersect more than one river meander, once the first point along the transect in each direction from the channel is reached that is higher than *h*, all further points are outside the width of the dam. The minimum width of the dam is then the number of points less than H meters above the stream bed that meet the above criteria multiplied by the transect point spacing. The method will match or underestimate actual dam width with a maximum error equal to twice the transect point spacing.

For the purposes of BCA development, I selected model resolutions that would allow for BCA calculation with a reasonable amount of computation power for a laptop. If the model were to be used for decision-making, I would recommend increasing the resolution to the maximum allowed by the DEM, which is in this case the limiting input for accuracy.

The table below compares the values I used to model dam structures for the proof-of-concept implementation vs those recommended for implementation by decision-makers and analysts:

Table 3 – Parameters used for dam width simulation. Proof-on-concept resolutions are lower and were used to make processing time reasonable for model development.

Parameter	**Proof-of-Concept used herein**	**Recommended for maximum accuracy**
Transect Spacing Along Channel	3 m	1 m
Transect Width	60 m	Maximum practical width. Wider dams provide fewer points of failure for dam complex destruction and reduce resources available to build greater numbers of smaller dams, which are more resilient.
Transect Resolution Perpendicular to Channel	1 m	1 m

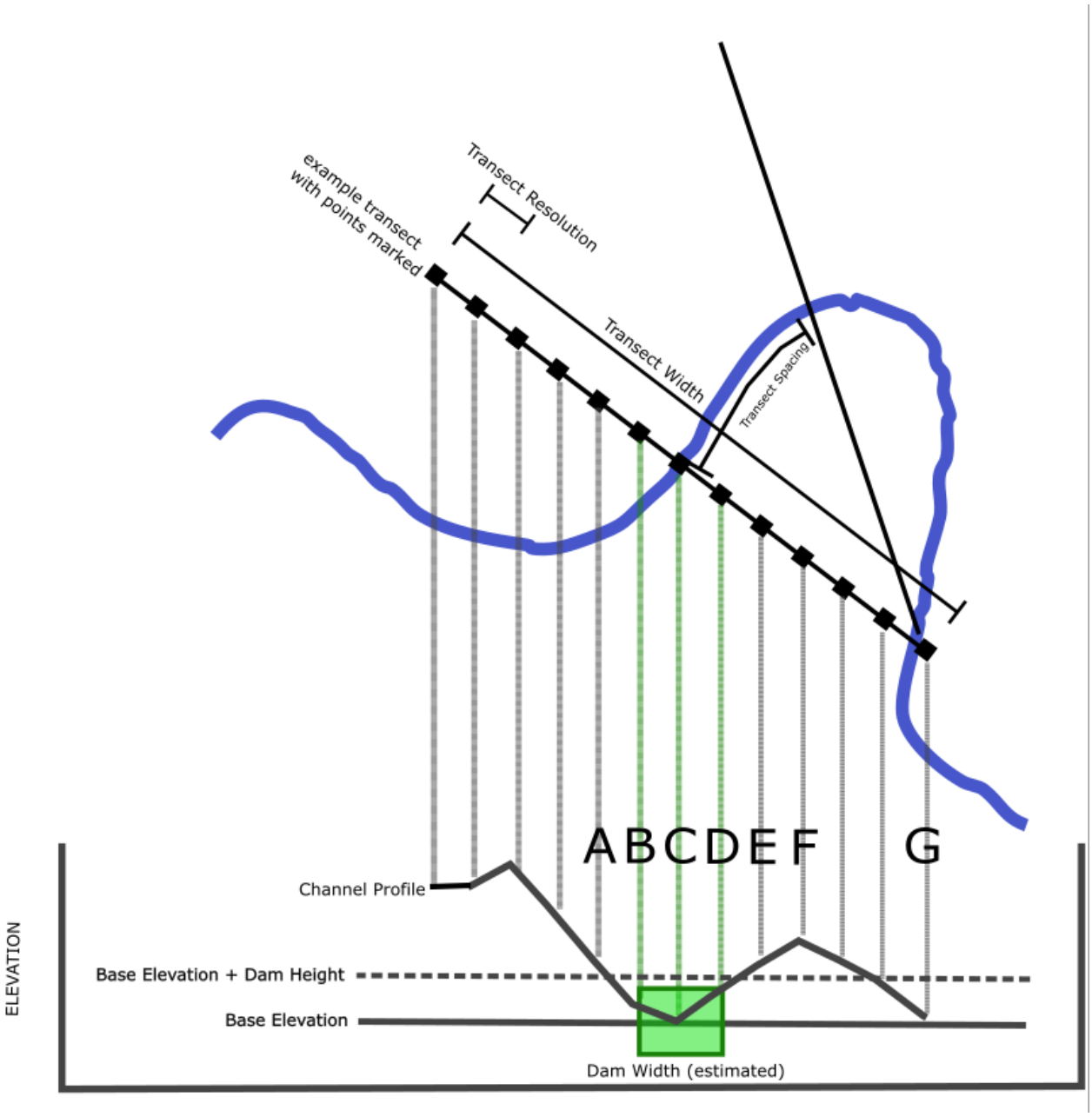

Figure 12 –Diagram describing transect analysis to determine dam width for each dam (see text for explanation).

The implementation of the dam structure model, shown in Figure 12, works as follows (letters refer to labels in Figure 12):

Transects with a fixed width are created so that each transect intersects a simulated dam perpendicular to the stream channel. Points are created along each transect at a constant spacing with an equal number of points on each side of the stream. The elevation of each transect point is extracted from the 1-m DEM. Then, point elevations are compared to the base dam elevation in the stream bed moving out from one side of the channel at a time. For each side of the channel, points are marked as "inundated" by the dam if they are within the vertical distance h (dam height) of the base elevation, until a point is encountered that is higher than the dam. At that point, all remaining

points on that side of the channel are marked as “not inundated” and processing occurs for the other side of the channel. In this example, starting at C, B is added, but not A. On the right side of the channel, D is added, but E is not because it is higher than the dam height above the base elevation. F and G are not considered because a point closer to the channel on that side has already been disqualified. The result is a database of points for every transect with a field denoting whether a given point is included in the BDA. The dam width can then be calculated by multiplying the number of inundated points by the transect point spacing.

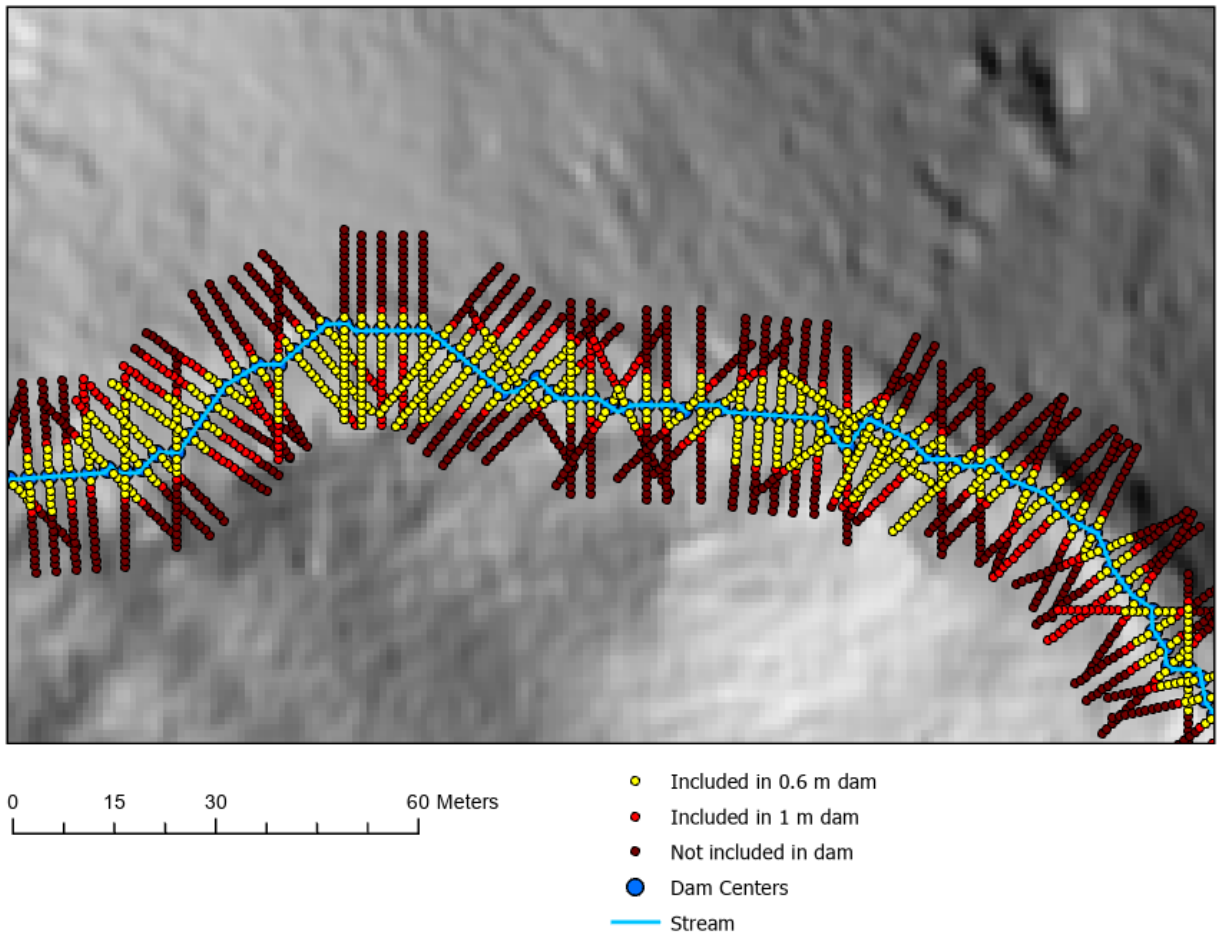

Figure 13 – Example dam width calculation results for 1 m dams in the study area with a hillshade background for reference. Red points on each transect were determined to be within elevation range of the 1 m dam, yellow points were within the elevation range of the 0.6 m dam and that of the 1 m dam (between the elevation of where the dam intersect the channel and that elevation plus the dam height). With a transect point spacing of 1 m, the number of red points in a transect is equal to the width of the dam (otherwise the width would be the number of dam points times the transect spacing). As expected, taller dams can reach further across the valley floor. Note that some dams would extend past the end of the transect (red points all the way to one or both sides of the transect), these are not considered in further analysis because the transect with should be selected based on the maximum dam width the user thinks would be feasible.

Calculating Working and Travel Time

Installing a BDA requires planning the structure, cutting and transporting construction materials, sharpening and driving in stakes, and, finally, weaving woody material through the stakes to create a semi-permeable structure. One of the limiting factors when selecting dam installation sites is the availability of local construction materials. BDAP does not consider this factor because BRAT

stream segments able to support pervasive dam densities by definition have vegetation available; the presence of vegetation was determined by Macfarlane et al. (2015) using LANDFIRE, a vegetation dataset with a 20 m resolution covering the continental United States and produced by the US Forest Service.

Since the availability of and distance to construction materials is accounted for, BDAP assumes that the time required to complete a dam is directly proportional to that dam's width and height. Data on BDA construction rates have not been systematically compiled. However, I was able to find some information to get an estimate; the value used would need to be calibrated for the region and available labor force in any case. Wheaton et al. (2019) (page 13) suggest that BDAs take "45 minutes to half a day" to construct, depending on the width and height, but does not mention the size of the crew. A time-lapse video on a Wyoming-based nonprofit's website (Wildlife, 2024) shows a team of 8 installing five 5-m wide BDAs over the course of five hours, suggesting that 8 people can build 5 m of BDA per hour. This is equal to one person building 0.625 m of beaver dam analog per hour. However, this was a volunteer crew; based on personal experience, I would expect a professional crew to work twice as fast. For simplicity, I assumed a rate for 1-m tall dams like those shown in the video of 1 m per hour. Since 0.6 m tall dams require the same number of posts to be driven, but less material to be gathered and woven between the stakes, I would expect a per-hour rate difference less than would be expected if directly proportional to dam height. For 0.6 m dams I decided to use a rate of 1.5 m per hour for construction time.

Since crews work in working-day segments rather than continuously, crews must travel to and from the site each day. The more time required to reach the site, the less time is available to work on the BDA. For this study, we chose the 10-hour working day common to natural resources labor crews, which typically work four ten-hour days per week.

For a single dam, the total amount of time that can be spent working on a site per day is equal to 600 minutes (ten hours) minus twice the travel time to reach the site. Once the number of hours required to just install the BDAs (ignoring travel time) is calculated, the actual time required can be determined by dividing the hours required to build the BDAs by the daily working hours for that site. If there are, for example, 26.5 hours total required, and the time to reach the site is 1 hour, we would expect construction to require 3 full days of work (2 hours of travel and 8 hours of work per day, totaling 24 hours of work) plus an additional day's travel and the remaining 2.5 hours of work. Thus, the total time required to complete 26.5 hours of BDA work is 32.5 hours. This relationship is shown in Equation *3*. Obviously, travel uses up an increasing proportion of the time, rendering projects that take multiple hours to reach inefficient from a time-use perspective. The details of how this calculation is used to determine the number of hours required to complete an entire cluster are described in the section titled *Benefit Cost Analysis: Dam Clustering and BDA Complex Recommendation*.

Equation 3: $$Total\ Time\ Required = \frac{BDA\ Installation\ Time}{working\ day\ length - travel\ time} + remaind. + travel\ time$$

(Equation 4)

I initially intended to include a crew size variable in the model that would consider differences in the number of people working. I thought this might affect the ratio of travel time to construction time for each dam cluster, but realized that that would only be the case if the last day of construction did not require a full day (thus reducing the amount of construction work done that day relative to the travel overhead to and from the site), and the crew could not be reduced in size to more closely match the remaining amount of work. A smaller crew would be sent on the last day, or the crew could continue working on the next dam cluster. Thus, I decided to leave the crew size out of the model. Since the model only considers the number of person-hours needed, and not the actual project duration, one person completing a combined 40 hours of work and travel time over an entire week is equivalent in the model to 5 people doing 8 hours of work and travel time over just one day. Project managers would decide how to implement the BDA cluster with labor.

Benefit Model: Simulating Inundation

The benefit provided by installing a BDA in each stream reach is assumed to be directly proportional to the area flooded by the creation of a BDA. While the likelihood of dam survival for long enough for beaver colonization to occur should impact the potential benefit, this factor is already accounted for in the BRAT results, which take into account stream power and likelihood of dam destruction (Macfarlane et al., 2015); since we are filtering for only segments modeled in BRAT as supporting pervasive beaver dam presence, it is assumed that conditions in these segments are conducive to reasonable dam survival rates.

The process for calculating the geometry of the area flooded by each dam makes use of several spatial analysis tools in ArcGIS Pro (Figure 14). The processing is resource-intensive and is the limiting factor in the number of possible dams that can be analyzed by BDAP.

The following process is repeated for each dam under consideration:

1. For each simulated dam, the model retrieves the location and the height of the dam. Since the dams were generated along the DEM-derived stream course, the dam is always within a DEM pixel representing the lowest point of the stream bed.
2. The dam location is buffered by 100 meters. This buffer is later used to clip the flow direction raster and the DEM to reduce search radius and processing time for the remaining steps. As a result, ponds greater than 100 m in length are not fully considered. The largest pond in the results was 127 m across, corresponding to a buffer of 63.5 m, so no ponds were cut off by the buffer in the scenarios tested herein. Processing time increases with the square of buffer radius, so it is very sensitive to increases in the search radius.
3. The watershed tool in spatial analyst is used to determine all cells within the clipped flow direction raster that are upstream of the dam point.
4. Next, the DEM is clipped by the buffer.
5. The watershed tool output, which is a raster, is converted to a polygon and that polygon is used to further clip the DEM, leaving only parts that overlap with the watershed boundary.

6. The maximum elevation flooded by the dam is calculated by adding dam height to the elevation of the stream channel the dam point. The clipped DEM is reclassified so that all values greater than this elevation are set to 0 and all values less than or equal to the elevation are set to 1.
7. Finally, the reclassified raster is converted to a polygon. That polygon is assigned the dams unique ID and added to the inundation geometry database.
8. Calculate geometry is used to calculate the area of each pond in square meters.

This technique is efficient but does have one shortcoming – the simulated inundation area does not include raster cells that are upstream of the dam structure but drain across it, rather than draining to the point where the lowest part of the channel intersects the dam. After reviewing the results, it became apparent that, for most ponds, these cells represent only a small fraction of the area of the resulting pond. The impact on pond area would be greatest for small ponds – fortunately, these ponds are not as desirable from a BCA perspective, and many are eliminated from consideration by the minimum pond size cutoff (discussed in the following section). Therefore, for the sake of making processing time more reasonable for the proof-of-concept and my student-level hardware, I decided not to implement the fix, which would require the watershed to be calculated separately for each point along the dam crest, and then the maximum bounding watershed used as input to the reclassification tool. In applied use, I would recommend implementing this improvement to improve accuracy of results, especially for small ponds where regions draining across the dam instead of to the upstream stream channel may represent a larger fraction of the total pond area.

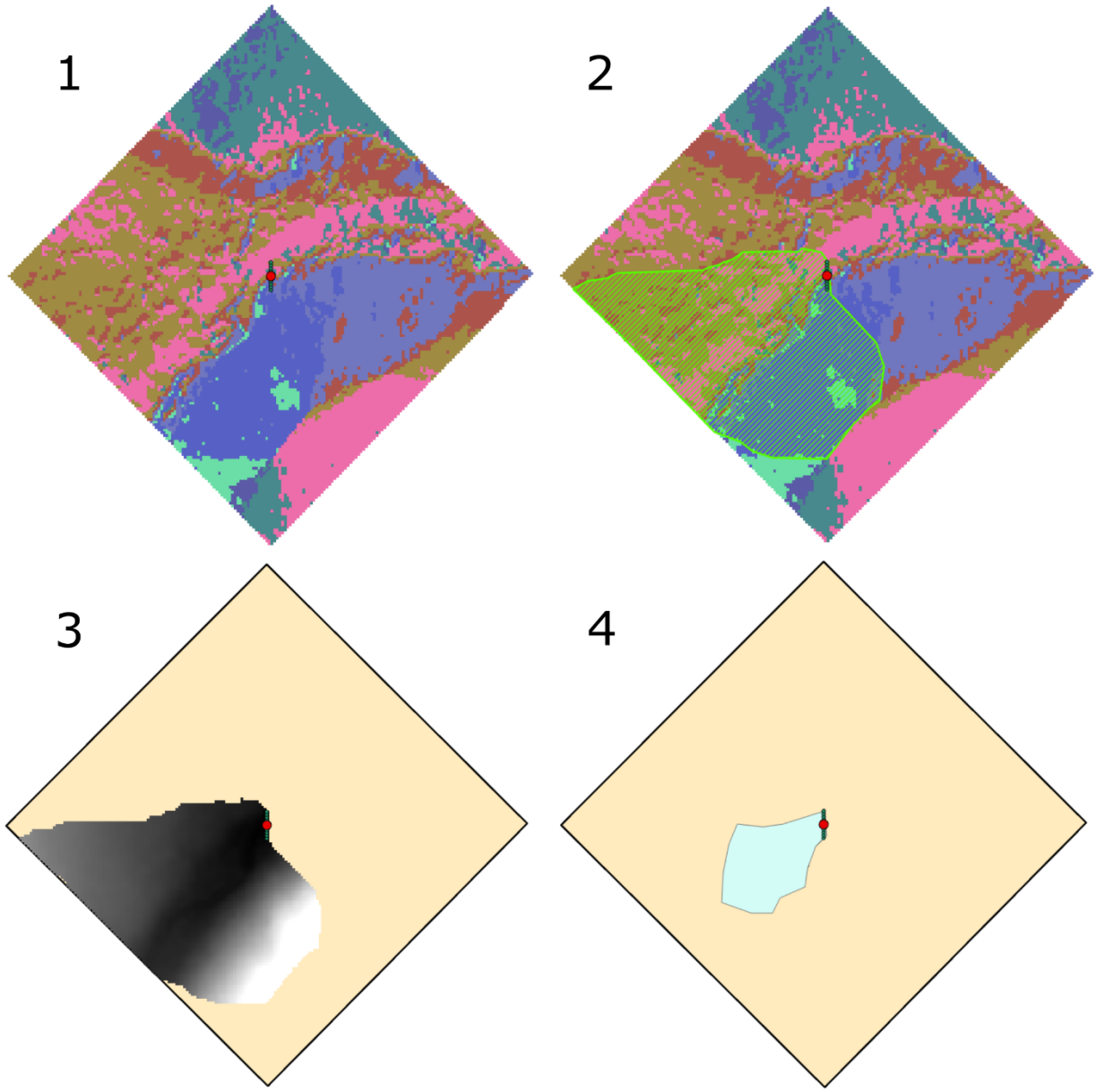

Figure 14 – Steps to simulating the area flooded by a BDA. First (1) a flow direction DEM that was generated for the entire study area (colors represent 8 possible flow directions from a cell on a DEM grid) is clipped to a diamond surrounding the location where the dam under consideration (green line) intersects the lowest point in the stream channel (red dot). Next (2) the watershed tool is used to extract that point's watershed boundary from the flow raster. This boundary will typically be cut off by the buffer edge. (3) the DEM is clipped so it only contains points within the watershed. (4) All points with values between the elevation of the point where the dam intersects the stream channel and that elevation plus the height of the dam (0.6 or 1 m in this study) are classified as 1, all other points in the clipped DEM are classified as NODATA. The resulting binary raster is converted into a polygon. This process is repeated for all dams in the dataset, creating a database of dams and associated pond geometries.

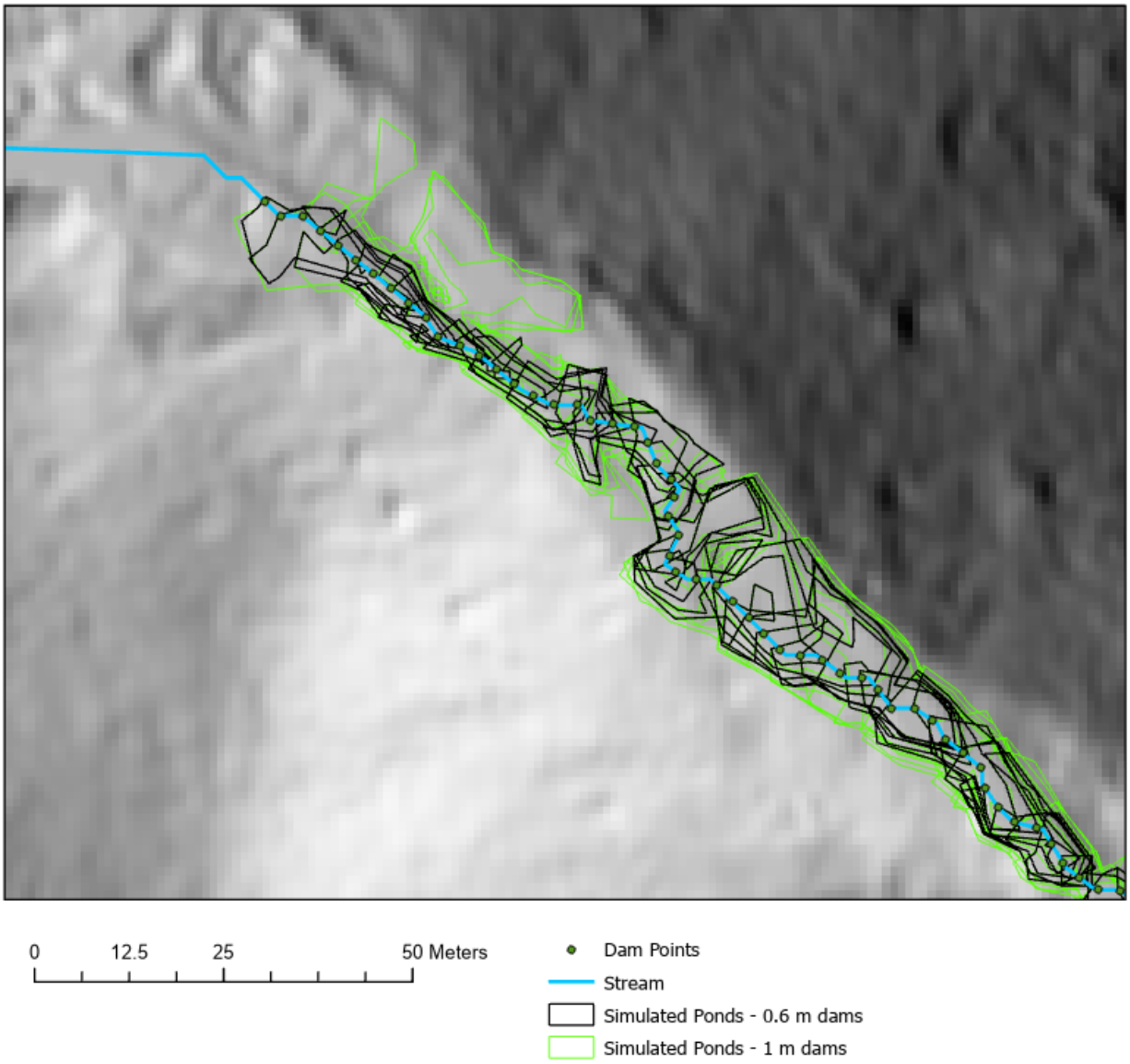

Figure 15 – Example of ponds generated using dams in the same locations with heights of 0.6 and 1 m.

Benefit Cost Analysis: Dam Clustering and BDA Complex Recommendation

The result of the benefit cost analysis described above is a set of all simulated beaver dam analogs with cost stored as the time to build the dam based on its width, and benefit measured by the area inundated by each dam. The dataset also includes the geometry of each BDA pond. However, effective BDA implementation requires a complex of beaver dam analogs within proximity to realize maximum benefits. Thus, the last step of processing is to build these complexes, referred to herein as "clusters."

In nature, mature beaver dam complexes consist of a continuous series of dams where the backwater of one dam reaches all the way to the base of the next dam. This provides beaver with

the ability to continuously be protected underwater while moving around and maximizes the ecological benefits of the complex (Allen, 1983, Dittbrenner et al., 2018, Jordan and Fairfax, 2022, Kornse and Wohl, 2020, Pilliod et al., 2018, Pollock et al., 2014). To create a BDA complex that mimics that natural tendency, we want to select sets of dams whose ponds do not overlap but have the minimum possible amount of space between them. Since planners will likely know the budget (and number of hours of labor) available to their crews, this factor will determine the number of dams in each complex. An additional factor, the search radius, is included to reduce processing time and constrain the length of the stream reach the cluster covers to a level where dams can be said to provide synergistic benefits. By creating complexes centered around each dam in the dataset we can see all combinations of neighboring, non-overlapping ponds.

Essentially, we are creating clusters of dams that satisfy the following criteria:

- Ponds within each cluster are as contiguous as possible.
- Ponds that have a sufficiently low size should be excluded from the cluster, as should ponds with impractically wide dams. Both these criteria are user inputs to the model.
- The total cost (time) required to build the cluster does not exceed the user-provided time budget.

This is accomplished as follows:

1. For each BDA in the dataset produced during the dam simulation phase, a script selects all dams within the search radius of the central dam that exceed the minimum pond size and do not exceed the maximum dam width provided by the user. It then calculates the distance to each of those dams and sorts the dams by distance.
2. Starting with the closest dam, the script checks to see if two facts are true:
    a. The pond associated with the dam does not overlap any ponds already within the cluster.
    b. The addition of the dam to the cluster does not cause the time required to build the entire cluster to exceed the time budget.
3. The first criterion is easy to assess using a precomputed dictionary associating each pond with the IDs of the ponds it overlaps, compiled using the *geom.overlaps* method in ArcPy. If there is no overlap, the second criterion is then considered. If an overlap is present the pond is ignored and the next pond in order is considered.
4. The second criterion requires keeping track of total project time. Project time includes travel time and construction time. Construction time has already been calculated for each dam. Travel time for the project depends on the total number of project hours. In this case, we make the simplifying assumption that the travel time to the central dam is representative of the entire cluster. Total complex completion time is equal to

$$T_{complex} = \sum t_{construction} + \left\lceil \frac{\sum t_{construction}}{D - 2t_{travel}} \right\rceil x 2t_{travel} \qquad (Equation\ 5)$$

where $t_{construction}$ is the total construction time of all dams in the complex, t_{travel} is the travel time needed to reach the complex, D is the maximum length of the working day (assumed 10 hours herein), and $\lceil a \rceil$ is a ceiling function that finds the closest integer to a that is greater than a.

5. Tcomplex can be recalculated easily each time a new dam is considered, including the dam under consideration. If it then exceeds the project maximum time, the dam is not added, and the complex is marked as complete. Otherwise, the dam is added, Tcomplex is updated to reflect the new dam, and the overlap list is updated to include any new overlaps with the new dam.
6. Once all the complexes are created, the total benefit of the complex and other ancillary statistics (such as number of dams or total dam width to build) can be calculated for each complex.
7. Finally, a series of non-overlapping complexes ordered from high to low BCR can be created using a similar overlap-detection process. This allows decision-makers to identify a set of projects that do not overlap and provide maximum benefit.

The final result consists of clusters of dams along with associated ponds, dam geometries, overall cluster benefit cost ratio, and actual cost in time to complete each cluster. End users can then further filter clusters based on criteria such as focus area, land ownership, stream order, etc. to determine which of the complexes that are feasible have the greatest BCR.

Results: 1 m and 0.6 m BDA complex simulation

To test the model, I ran it on the King Solomon Creek drainage with two different dam heights: 0.6 m and 1.0 m. These heights are representative of the high and low end of the height range of the actual beaver dams BDAs are emulating and are associated in the model with construction rates of 1.5 m and one horizontal meter per person-hour, respectively. I clustered the dams with maximum width cutoffs ranging from 5-30 meters in increments of five, hoping to determine whether a certain dam width was associated with higher BCA complexes. In summary, I completed twelve runs using two different dam heights and 6 widths.

The following table includes the additional model parameters, which remain constant between model runs.

Table 4 – Parameters used for dam simulation and clustering.

Parameter	Value	Note
Minimum pond size	20 m^2	Ponds smaller than this are ignored when building clusters.
Labor Crew Size	10	
Potential BDA Spacing	3 m	
Stream Transect Point Spacing	1 m	
Stream Transect Length	30 m	
DEM Resolution	1 m	
Travel Time Raster Resolution	1 m	
Maximum Cost Per Cluster	24000	10-person crew working a full week (40 hrs.)

Minimum # Dams Per Cluster	4	Clusters that reach max cost with three or fewer dams excluded from results; this ensures that clusters are resilient to destruction by flooding.
Clustering Search Radius	100 m	Only dams within one hundred meters of the central dam of each cluster are considered. This parameter should be chosen to represent the greatest distance between dams considered in the same cluster.

Dam Simulation Results

The first component of the model, and one which underlies all further analysis, is the simulation of individual BDA along the stream channel, in this case placed every three meters. The primary outputs are the width of a dam of a given height required to create a pond with the associated surface elevation, and the geometry of that pond. These outputs are then used as inputs to clustering analysis. 12,305 dams were modelled for each dam height.

Figure 16 summarizes the attributes of the modelled dams for 0.6 and 1 m dams. Panels A/B show the distribution of simulated dam widths. As expected, greater dam heights are associated with wider dams. The distribution of 1 m dam widths has a peak at the uppermost end of the range; this is likely associated with dams that would have been wider than the selected transect width (30 m) but were cut off because of the selected width. All dams that would be in the tail of the distribution are therefore concentrated in the 29 and 30 m bins (29 bins due to a rounding error discovered during results analysis).

Panels C/D show the distribution of pond areas for each dam height. For both heights, pond areas exhibit a right-skewed distribution, where most ponds are quite small compared to the largest ponds, which could exceed 1,000 m^2. The right tail of the model contains more dams for the 1 m dams. The median pond area for 0.6 m dams was 50.8 m^2, while for 1 m dams it was 122.6 m^2

Panels E/F show the results of the travel time model, which was run for each dam simulated. The histograms are identical for both sets of dams since the dam locations did not change.

Finally, Figure 17 shows the relationship between dam width and pond area for both dam heights.

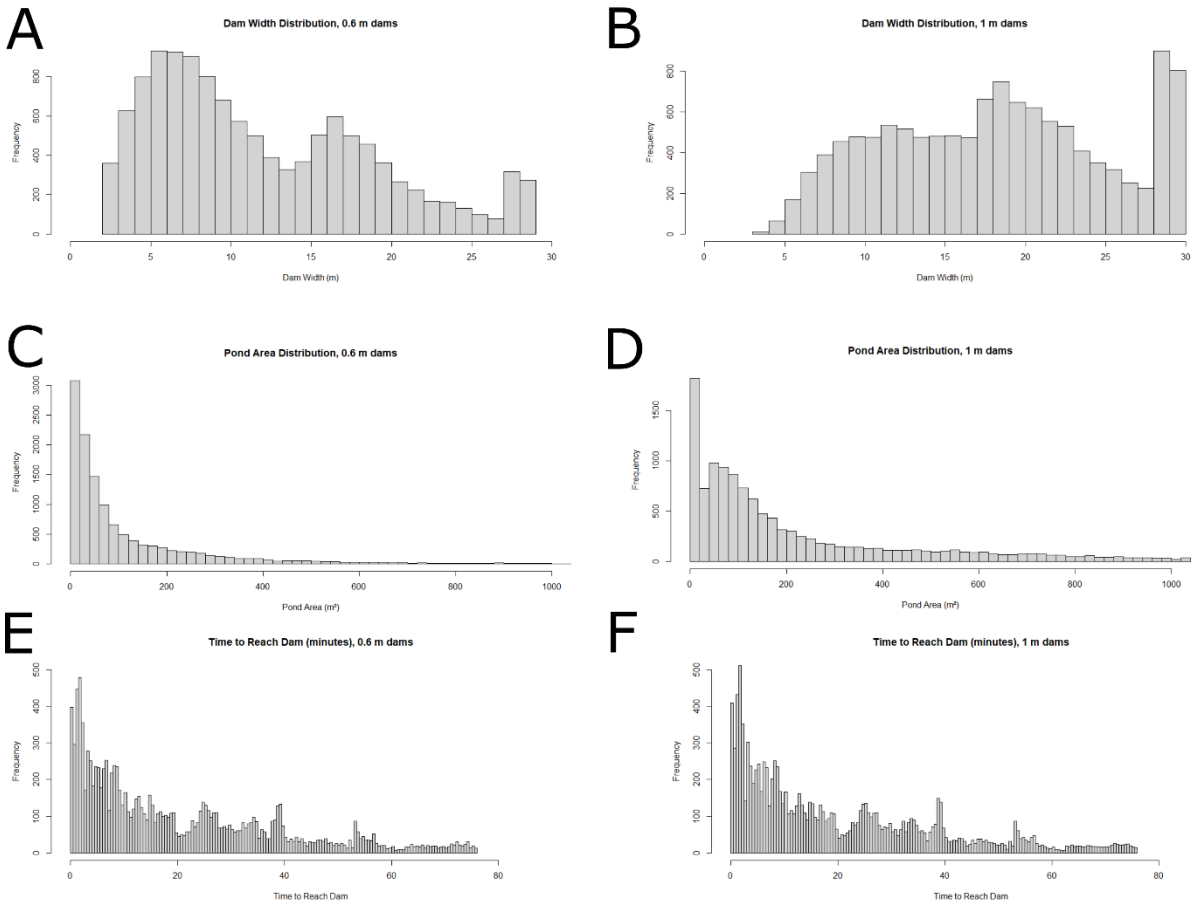

Figure 16 – Numeric summary of the results of dam simulation.

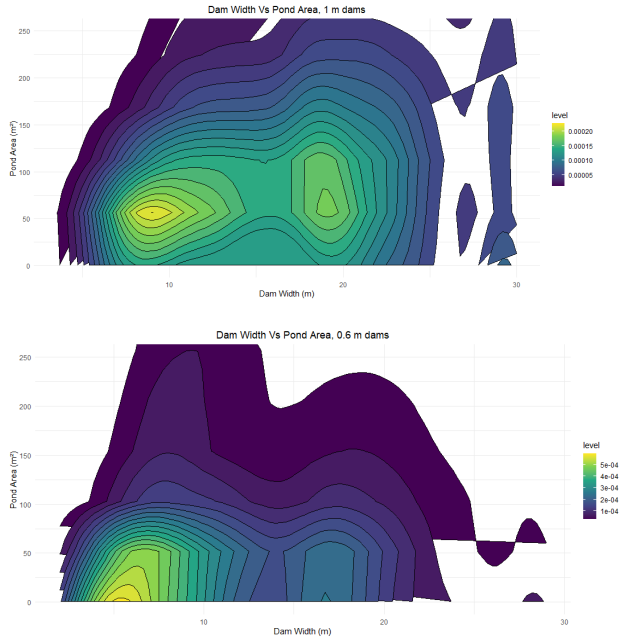

Figure 17 – Density plot for 12,305 dams plotting pond area against dam width.

BDA Clustering Results

Clustering was completed with the parameters described in Table 4.

The minimum pond size of 20 m resulted in the elimination of 3083 dams (25%) from the 0.6 m dataset and 1821 dams (14.7%) from the 1 m dataset. In addition, dams with a width exceeding the maximum width parameter were not considered during each cluster analysis.

The results of cluster analysis are summarized in Figure 18, which plots a variety of results obtained by running cluster analysis on each set of dams and varying the maximum dam width parameter. The average BCR plot shows that for both sets of dams, BCRs (benefit cost ratios) of the clusters tends to be highest for low to moderate maximum width parameters (no BCR data is available for the 1 m dam with a maximum width of 10 m because no clusters contained the minimum of four dams). It also shows that the lower, 0.6 m dams tend to provide more advantageous BCRs at all maximum widths.

Average cluster benefit and average cluster cost show that higher dams have greater costs than lower dams for all maximum widths, but that actual benefits are higher for lower dams at smaller maximum dam sizes.

Average pond area increases with increasing maximum dam width for both datasets, although pond area increases more quickly with wider dams for 1m dams. However, this is offset by the fact that these model runs result in a smaller number of dams.

The percentage contribution of travel time to the total time cost was very similar for both dam sets. As larger dams are allowed, the amount of travel decreases slightly. The contribution of working time to the cost varies inversely.

The number of ponds that could be added before the maximum cost was exceeded was always greater for smaller dams, which makes sense these are faster to build. At high maximum dam widths, the total cost was not exceeded because the search radius was not large enough, which explains the trend of decreasing numbers of ponds as maximum width is included (wider dams result in longer ponds which cause the cluster to saturate the search radius more quickly).

The total number of dams run, which is the number of dams that passed the minimum pond size and maximum width filters, was generally greater for the 0.6 m dams. This is because the average length of shorter dams is less because valley transects are shorter at lower distances above the stream channel. Therefore, taller dams are more likely to exceed the maximum dam width. At high maximum widths, 1 m dams begin to exceed 0.6 m dams in number because wide 0.6 m dams are more likely to produce ponds smaller than the minimum size threshold at greater widths.

The number of unique clusters was greater for 0.6 m dams at most heights, likely because more combinations of small dams can fit within the search radius.

The number of non-overlapping clusters is the number of clusters from the results that could be built in order from high to low BCR without creating any overlapping ponds. It is always greater for smaller dams – again, smaller dams can be used more effectively to fill in spaces between ponds in existing clusters. Note that the number of non-overlapping clusters is about two orders of magnitude less than the total number of unique clusters.

The remaining plots compare the top ten clusters for each dam height and maximum width. Since many organizations are likely to build only a small fraction of potential BDAs, comparing the top performers allows for a more realistic understanding of the actual BCR implications of each maximum width and dam height.

The most important is the top ten overall BCR plot. This shows the overall BCR for the entire project if the project consisted of the ten clusters with the best BCR ratios. Therefore, it is essentially the average of the BCR ratios weighted by the contribution of a given clusters cost to the total project cost. The plot shows that the average BCR for top ten clusters is greatest for 0.6 m dams with small maximum widths, and that overall top 10 projects for 0.6 m dams have an overall BCR 1.2-1.5 times greater than top 10 projects for 1 m dams.

Figure 18 – Results of clustering analysis for 0.6 m and 1 m dams. These plots represent all clusters, even those that overlap.

Discussion

General Implications for BDA Placement

Although it is difficult to generalize to different study areas, several trends in the outcome of BDAP simulation may have wider implications for the installation of BDA, which could be investigated in future work.

First is the fact that dams with smaller minimum widths tend to perform much better in terms of BCR under clustering. One hypothesis to explain this pattern is that excluding wider dams makes it more likely that clusters will include dams placed on natural narrow points along the valley floor that are ideal for creating large ponds using small dams. In contrast, when wider dams are included, they are likely to create longer ponds that will inundate possible narrow points, removing them from consideration during clustering analysis.

Second, the right skew of the pond area charts for both dam heights (Figure 16 panels C and D) shows that most of the potential benefits to be realized in the watershed could be provided by a small proportion of the possible dams. This shows the importance of using a geospatial decision support system to find the best locations for installation; manual examination of thousands or tens of thousands of potential dam sites would be difficult and impractical.

Third, shorter dams tend to be associated with superior BCRs than taller dams. This is surprising given the dam construction rates chosen for the model. The ratio of the chosen construction rates (40 minutes per meter and 60 minutes per meter) between short and tall dams is 2:3 (67%), but the ratio of heights is 3:5 (60%). This should theoretically give tall dams an advantage because they are cheaper to construct compared to the pond depth they provide. Despite this, shorter dams outperform taller ones across the board. One explanation could be that there is a scale-dependent effect, where landscape features in the study area tend to cluster into certain size ranges. For example, perhaps the natural floodplain in many of the dam locations contains wide flat areas at heights of 0.6 m above the stream channel, but heights of 1 m tend to be located outside the floodplain in steeper terrain. Given the small scale of streams in the basin, this explanation seems plausible.

Implications for BDA Installation in Study Area

Based on the observations discussed above, resource managers in the study area should optimize their projects by instating a maximum dam width of 10 m and a dam height of 0.6 meters.

In addition to the general conclusions we can draw about optimal BDA cluster design, we can draw specific conclusions about the ideal placement of BDA clusters within the study area. Figure 19 shows the average BCRs of dams located within cells of a hexagonal grid along the stream channels (where BRAT predicts pervasive dam density). It is immediately apparent that BCRs tend to cluster geographically. Specifically, upper reaches of streams located in more mountainous terrain, such as those in the western and southern part of the study area, tend to perform more poorly, while those in broad valleys located on the main stem of King Solomon Creek along the northeastern margin of the study area perform well. While it is true that a road follows the main fork (Figure 7), this is unlikely to be the reason for this difference, given that only 5-7% of the cost of the average cluster is associated with travel time from the nearest road (Figure 18). In study areas with fewer roads, or where dam construction times are less, the costs of travel might increase in their contribution.

Figure 20 and Figure 21 contain maps showing the top four BDA clusters for each dam height with a maximum dam width parameter of 10 m. The top left cluster, which was rated as having the best BCR for both dam heights at the same location, illustrates the need for local managers to review the top-scoring ponds manually. In this case, the BCR was extremely high because there was already an existing artificial dam structure within the cluster. The small spillway of the dam was included in the DEM when it was created, creating a narrow spot in the channel with a large basin above it. The outlet width is only 5 meters, but based on the valley just below the dam, if the dam wasn't present, we would expect a similar dam width but a much smaller pond, since the BDA would only have a height of 1 m or less, whereas the artificial dam currently present has a height of 5.5 meters. In

conclusion, decision-makers would certainly discard this top result since building a BDA within existing water infrastructure would not be acceptable.

The remaining locations are feasible for both dam heights. All the remaining clusters contain a moderate number of long ponds with narrow dams. We can see that the number two cluster for 1 m dams is in a similar location to the number three cluster for 0.6 m dams; this is likely due to the morphology of the valley floor, which is very broad and flat, and may already contain some beaver structures. The proximity of the road may also provide a slight boost to the BCR since travel time is negligible. The fact that the meadow may already contain actual beaver structures points to the limitations of the BDAP model – it is dependent on the user to decide where analysis should be conducted (beaver ponds also already appear to exist in the third best pond for 0.6 m dams); in actual use, it would be beneficial to remove stream reaches that already contain healthy beaver ecosystems from the input dataset just like areas without "pervasive" BRAT scores were removed herein. The identification of areas where beaver have already been active suggests that BDAP does capture some of the landscape attributes that would make BDA-based restoration effective.

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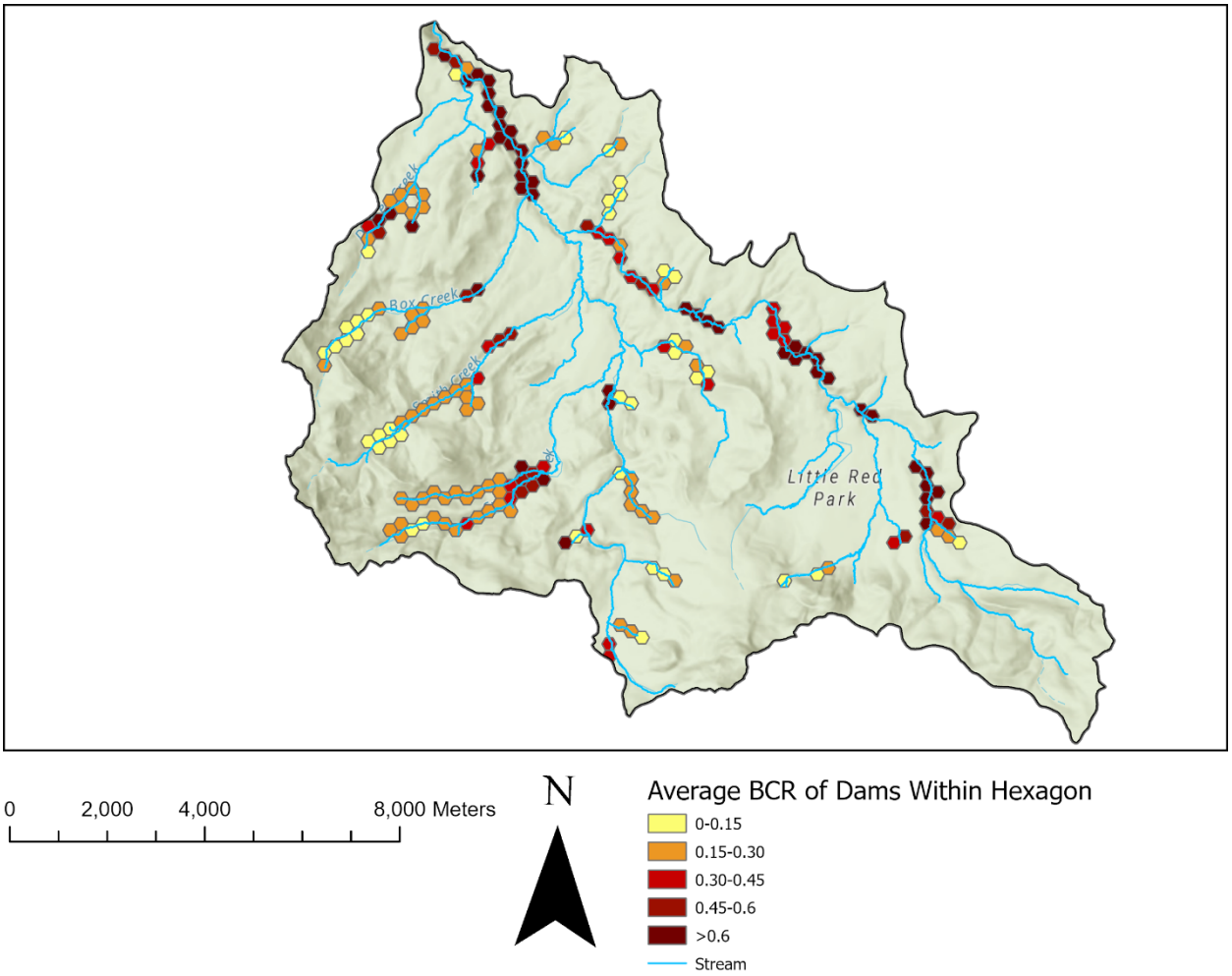

Figure 19 – Average BCRs of potential BDAs within hexagonal grid cells applied to stream reaches rated as supporting "pervasive" dam densities by BRAT.

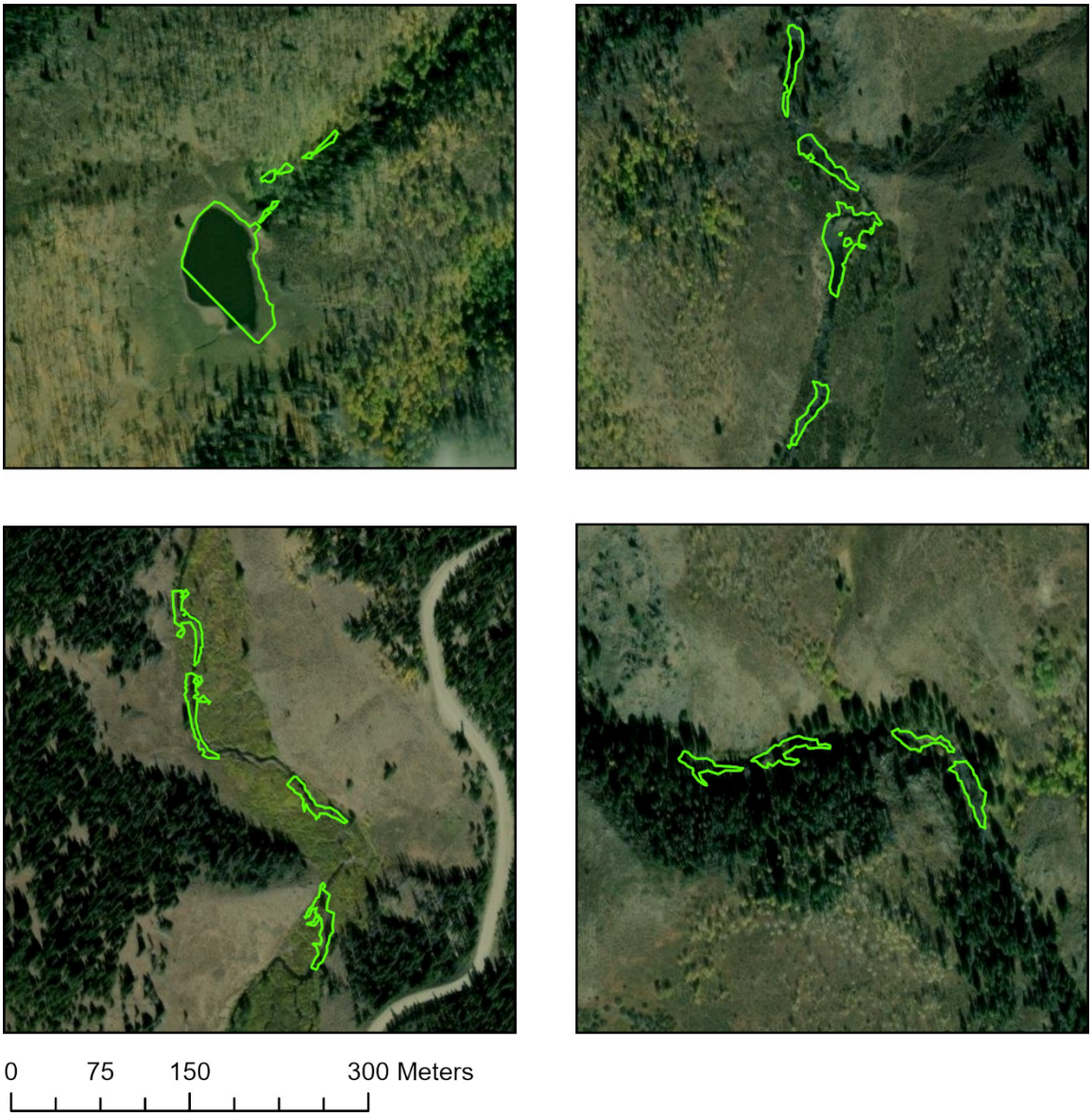

Figure 20 – Top 4 modelled non-overlapping pond clusters by BCR for 1 m dams and 10 m max width, in descending order clockwise from top left. Cluster BCRs are 1.52, 1.24,0.94, 0.85.

Figure 21 - Top 4 modelled non-overlapping pond clusters by BCR for 0.6 m dams and 10 m max width, in descending order clockwise from top left. Cluster BCRs are 2.48, 1.84, 1.34, 1.18.

Potential Model Improvements

As a pilot model, BDAP has brought to light many of the topographic and geographic factors that affect the cost-effectiveness of BDA clusters. Like any decision-support model, it only considers some factors out of the many that could go into the decision-making process. Over the course of this work, I identified several areas for further study and improvement for the continued development of BDAP.

First, the model could implement more prefiltering of stream segments to be analyzed. This could include things like the elimination of stream reaches with existing beaver complexes, as well as other filters such as property ownership. Beaver complexes could be detected using remote sensing data using spectral analysis or machine learning (Fairfax et al., 2023, Zhang et al., 2023).

The cost model could be improved by implementing a network analysis model of travel time from the work crew's actual base location by vehicle; in this small watershed, travel by road would not be a major contributor to site travel time, but in a larger region, it would come into play. It could also be improved to allow the user to specify a range of potential dam heights to be optimized for the best BCR for each dam; however, this would add another dimension to the model and increase processing time.

The benefit model could also be improved in several ways. First would be implementing improved modelling of pond inundation by calculating watersheds for all points along the dam crest, rather than only the point where the dam intercepts the stream channel. This would be a simple fix to ensure points upstream of dams with flow paths that reach the channel downstream of the dam crest, but pass through the crest, would be improved in the modelled pond area.

A second potential improvement to the benefit model would be to discount the benefit of a dam cluster by the likelihood of the cluster being destroyed in a flood event. This would be based on a model predicting maximum stream power and relating the likelihood of individual dam failure to stream power (Hafen et al., 2020, Butler and Malanson, 2005). The probability of dam failure could then be used to discount the benefits of a given dam and, in turn, BDA cluster. The protective power of having more dams in the cluster, which may reduce the probability of any given dam failing, should also be considered.

Third, a mechanism could be devised to consider the synergistic ecological benefits provided by more compact BDA clusters, where there is less non-inundated space between ponds. To do this, we could simply consider the number of dams or total flooded area relative to the length of a BDA cluster. However, a more sophisticated method would be to create a metric that could be used to assess the degree of compactness of BDA clusters and provide a bonus to clusters that are more compact. One such metric could be the percentage of the height range of a cluster that is occupied by inundated ponds. This is calculated by multiplying dam height by the number of dams in the cluster and subtracting the result from the range in elevation between the bottom of the lowest dam and the top of the highest dam.

Under this calculation, higher percentages of unoccupied elevation range are associated with lower densities of pond coverage within the cluster. The same calculation could be done for stream distance covered by ponds vs uncovered within each cluster. The results of these calculations

could be used to further adjust the benefit model in future iterations of the model, to reflect the greater ecological benefits of more contiguous pond coverage within a cluster.

Figure 22 shows the results of this calculation for 1 m dams. On average, 37% of the stream channel elevation range within a cluster is *not* associated with a flooded pond area, indicating an average pond coverage of 63%.

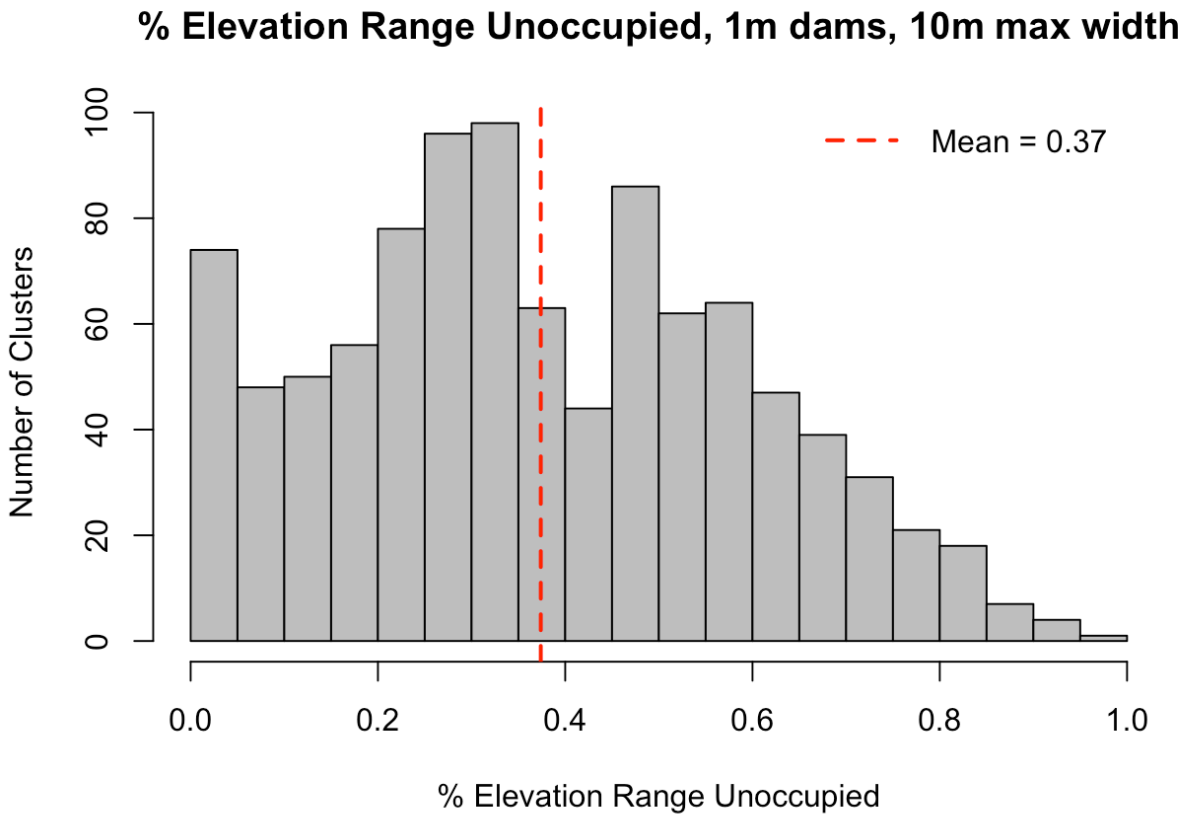

Figure 22 – Percent of elevation range of clusters of 1 m dams unoccupied by BDA ponds

Finally, validation of the model with real-world data would improve our understanding of its strengths and weaknesses. Unfortunately, there is no extant database of installed BDA; the use of BDA is still in its infancy, and federal agencies such as the USFS, which owns much of the land in the study area, have not made much use of the restoration method to date. If and when such a database exists, it would be informative to see if and how the actual placement of BDA differs from the idealized placement suggested by BDAP within the King Solomon Creek drainage.

Conclusion

This thesis presents BDAP (Beaver Dam Analog Prioritization), a cost-effectiveness-based model designed to help land managers identify the most effective locations to build cluster of Beaver Dam Analogs for stream restoration. Costs are modeled as the time required to reach and install clusters of dams, while benefits are directly proportional to the area flooded. The model simulates individual dams and then uses them to build and prioritize near-contiguous clusters of multiple BDAs.

BDAP was tested within the King Solomon Creek study area using two different dam heights and six potential maximum dam widths. The results show that, within the study area, dams with shorter lengths and lesser heights (widths of 10 m or less, heights of 0.6 m) tend to produce BDA clusters with more favorable benefit-cost ratios. They also suggest that BDAs are more cost-effective when built in broad, flat valleys rather than steep, narrow canyons.

While the BDAP model offers valuable insights, it has certain limitations. Future research should focus on enhancing the BDAP model by incorporating additional ecological factors and improving the accuracy of input data. Potential improvements include better pre-filtering of stream segments to exclude areas with existing beaver populations, implementing a network analysis model for travel time, improving the pond simulation model by accounting for cross-dam flow, and refining the benefit model to account for the likelihood of dam failure. In addition, a metric describing the compactness of BDA clusters could be used to further refine BDA clustering and prioritization.

BDAP contributes to the field of stream restoration by providing a practical tool for prioritizing BDA installation sites. The BDAP model demonstrates the possibility of using quantitative modelling of costs and benefits to inform decision-making about where to use limited resources to maximize the effectiveness of process-based, beaver-centric restoration.

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