January, 2013

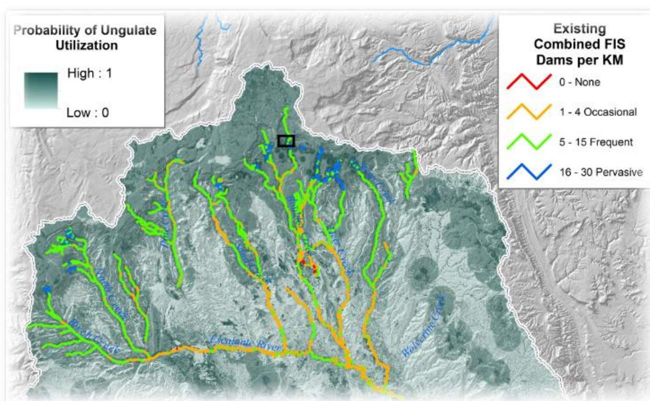
Modeling the Capacity of Riverscapes to Support Dam-Building Beaver : Case Study - Escalante River Watershed

Joseph M. Wheaton, *Utah State University*

MODELING THE CAPACITY OF RIVERSCAPES TO SUPPORT DAM-BUILDING BEAVER

CASE STUDY: ESCALANTE RIVER WATERSHED

FINAL REPORT TO THE GRAND CANYON TRUST & WALTON FAMILY FOUNDATION



Prepared by:

WILLIAM W. MACFARLANE, *Research Associate*

JOSEPH M. WHEATON, *Assistant Professor*

UtahStateUniversity
ECOGEOMORPHOLOGY & TOPOGRAPHIC ANALYSIS LABORATORY

JANUARY, 2013

EXECUTIVE SUMMARY

Beaver (*Castor canadensis*) dam-building activities lead to a cascade of hydrologic, geomorphic and ecological effects that increase stream complexity, which benefits a wide-variety of aquatic and terrestrial species. Depending on biophysical and vegetation conditions present, beaver dam-building activities variously trap sediment; raise incised streambeds, often reconnecting them with their floodplains; subirrigate the valley downstream of a dam; create wetlands; slow runoff; mitigate impacts by floods; extend seasonal stream flow; increase stream complexity; extend riparian woody and other vegetation; and create or increase habitat for diverse and sometimes rare species, including amphibians, fish, small mammals, and birds. As a result, beaver are increasingly being used as a critical component of passive stream and riparian restoration strategies. Using beaver as part of a restoration design is appealing because it is much less expensive than conventional stream restoration. As long as beaver have access to sufficient water, food and construction materials they can construct dams over an incredibly diverse range of climatic and physiographic conditions spanning from desert streams to alpine meadows. However, the capacity of the landscape to support such dam building activity can vary dramatically across these settings according to the flow regime and the availability of dam building materials.

In this pilot project, we developed a spatially-explicit model to assess the capacity of landscapes in and around streams and rivers (i.e., riverscapes) to support dam building activity for beaver. Capacity was assessed in terms of readily available nation-wide GIS datasets to assess key habitat capacity indicators: water availability, relative abundance of preferred food/building materials and stream power at base flows versus regular floods (i.e., 2-year recurrence interval flows). Stream power was calculated using USGS regional regression equations and calibrated to determine where dams could be built based on base flow stream power and persist from year-to-year based on two-year recurrence interval stream power. Fuzzy inference systems were used to assess the relative importance of these inputs which allowed explicit incorporation of uncertainty resulting from categorical ambiguity of inputs into the capacity model. Factors that can potentially limit beaver from realizing the full capacity to support dams include: 1) ungulate grazing capacity 2) proximity to human conflicts (e.g., irrigation diversions, settlements) 3) conservation/management objectives (endangered fish habitat) and 4) projected benefits related to beaver re-introductions (e.g., repair incisions). Future work will combine these additional inputs into a more all-encompassing model, which we call the Beaver Restoration and Assessment Tool (BRAT). This pilot project represents the first phase of development of BRAT.

We present a case study application from the Escalante River watershed in southern Utah, a diverse watershed that contains riverscapes ranging from desert canyonlands and washes to wet alpine meadows. Model validation/calibration was conducted in both the Escalante watershed and the Logan River watershed in northern Utah, an area where beaver dam census data and correlated stream power and beaver dam establishment and persistence data exist. Results indicate that beaver capacity varies widely within both study areas, but follows predictable spatial patterns that correspond to distinct ecoregions and vegetation communities. We show how the capacity model is a tractable rapid assessment method and decision support tool for inventorying watersheds to assess beaver dam building capacity. Because the models use freely and readily available nation-wide GIS data as model inputs, the model can be easily applied to other watersheds. If better quality, higher resolution inputs are used, more refined model predictions are possible. However, we illustrate how the capacity model can be used to help resource managers develop and implement restoration and conservation strategies employing beaver that will have the greatest potential to yield increases in biodiversity and ecosystem services. When this model is eventually combined in BRAT with other limiting factors and management realities, this could become part of a powerful suite of scenario building and planning tools.

Recommended Citation:

Macfarlane WW, and Wheaton JM. 2013. Modeling the Capacity of Riverscapes to Support Dam-Building Beaver-Case Study: Escalante River Watershed. Ecogeomorphology and Topographic Analysis Lab, Utah State University, Prepared for Walton Family Foundation, Logan, Utah, 78 pp.

Available at: http://etal.usu.edu/BRAT/

CONTENTS

LIST OF FIGURES

INTRODUCTION

Due to the suite of hydrologic, geomorphic and ecological feedbacks associated with their dam-building activities, the North American beaver (Castor canadensis; beaver) are widely recognized as ecosystem engineers (Burchsted et al., 2010; Gurnell, 1998; Naiman, 1988; Rosell et al., 2005; Warren, 1927). Depending on biophysical and vegetation conditions present, beaver dams variously trap sediment; raise incised streambeds, often reconnecting them with their floodplains; subirrigate the valley downstream of a dam; create wetlands; slow runoff; mitigate stream gouging by floods; extend seasonal stream flow; increase stream complexity; extend riparian woody and other vegetation; and create or increase habitat for diverse and sometimes rare species, including amphibians, fish, small mammals, and birds (Bartel et al., 2010; Medin and Warren, 1991; Stevens et al., 2007; Westbrook et al., 2006; Wright et al., 2002). Dam-building beaver can also mitigate diverse climate change effects because their dams slow water and sediment movement through landscapes, which leads to increased complexity of stream habitat through time and diversification of residence time distributions of water and sediment (Burchsted et al., 2010).

As early as the 1930's beaver began to be recognized for their ability to restore degraded ecosystems and were translocated to help control soil and water loss in degraded areas (e.g., Scheffer, 1938). For example in 1950, the Idaho Department of Fish and Game used parachuted beaver that were in wooden crates designed to release the beaver upon landing into remote terrain in an effort to control soil erosion and flooding (Mechanix Illustrated, 1950). Reports indicate that beaver "headed straight for water and started building dams within a couple of days." However, one issue that still remains to be addressed is how were the drop sites determined? It seems unlikely that in 1950 the drop sites were selected based on the landscape's capacity to support dam-building beaver.

The earliest efforts to evaluate and rank existing or potential beaver habitat for the western US began in the 1940's, but these early beaver habitat suitability studies were qualitative in nature (e.g., Atwater, 1940; Packard, 1947). Unlike many species of management concern, the habitat requirements for dam-building beaver are relatively simple to accommodate. As long as there is sufficient water, food and construction materials and stream flows that allow dams to be built and persist beaver can thrive under an incredibly diverse range of climatic and physiographic conditions ranging from desert streams to alpine meadows. The range maps of beaver in North America reflect this, showing they can exist pretty much anywhere in the lower-48. Some of the areas that were previously thought not to be within the range of beaver (e.g., parts of Nevada and California) have now been shown to have hosted both historic and modern populations. Within this enormous range, it is helpful to be able to better understand what areas might support higher densities versus just occasional presence.

Allen (1983) was one of the first to establish a quantitative habitat suitability index that evaluated the suitability of beaver habitat based on key environmental variables assumed to be affecting beaver populations. For riverine environments, Allen's (1983) model included stream gradient, average water fluctuation, percent tree canopy closure, percent of trees in various size classes, percent shrub crown closure, average height of shrub canopy, and species composition of woody vegetation. Other quantitative approaches followed that attempted to evaluate the relationship between beaver density and various physical, environmental and vegetative parameters using statistical analysis (Beier and Barrett, 1987; Howard and Larson, 1985). However, tests of these habitat suitability models have shown the assumptions to be too restrictive for this highly adaptable and non-discriminating aquatic rodent (Emme and Jellison., 2004). Like other generalists, beaver defy traditional habitat suitability models that attempt to develop empirical habitat suitability curves on the basis of where beaver are found and combine those curves into global models. Resultant habitat suitability models fail to fully delineate beaver habitats and the correlation between the suitability classes and beaver occurrences or densities tended to be weak or non-existent (Jarerna, 2006). Despite these limitations of the habitat suitability approach it continues to be the common method for gauging beaver potential.

Figure 1 – A beaver actively working to maintain its dam. Photo by Cadel Wheaton.

Beaver are increasingly being used as a critical component of passive stream and riparian restoration strategies. The restoration efforts are primarily in the form of beaver recovery (Andersen and Shafroth, 2010; Andersen et al., 2011; Burchsted et al., 2010; Wolf et al., 2007) or live trapping and relocating nuisance beaver to areas where they can be used as a passive restoration tool (Albert and Trimble, 2000; Macdonald et al., 1995; McKinstry et al., 2001). Efforts are also underway to use beaver to buffer impacts of climate change (Hood and Bayley, 2008a). Hood and Bayley (2008a) report that beaver dramatically influence the creation and maintenance of wetlands even during extreme drought. Beaver dams also increase water retention time which is thought to facilitate ground water recharge (Pollock et al., 2003). In light of climate change forecasts for the southwestern US that predict increased temperature, precipitation events of increasing intensity, and a growing potential for mega droughts (e.g., Schwinning et al., 2008; Seager, 2007), reintroducing beaver should be considered as a viable means to mitigating climate change.

Pollock et al. (2012) are attempting to "partner with beaver" to reconnect the incised and degraded channel of Bridge Creek, eastern Oregon with portions of its former floodplain to increase stream habitat complexity and the extent of riparian vegetation with the hopes of improving Endangered Species Act (ESA)-listed steelhead (Oncorhynchus mykiss) habitat. The problem in Bridge Creek was that dams constructed within the incised channel bare the full force of floods because these floods are entirely contained within the channel and dam crest elevations are generally not high enough to spread flows out over a broader floodplain and dissipate that energy. Consequently most dams fail within their first season. The restoration treatment involves installing wooden fence posts across the channel at a height intended to act as the crest elevation of an active beaver dam. Within months of installation, beaver began occupying structures. After three years of monitoring, and being subjected to numerous high flows both the structures maintained by beaver and those maintained artificially are lasting longer than other dams and invoking much more dramatic geomorphic responses. Many of the 100's of dams have filled to the brim with sediment and formerly dry terraces are now active floodplain surfaces and in some places have even become wetlands that are inundated year round. The restoration design was summarized in Pollock et al. (2012), and a series of reports and papers are in preparation that will start to disseminate the restoration response findings.

In light of the increased use of beaver as part of a variety of restoration strategies and some of the early successes, it is easy to see why there is so much excitement for using beaver. Compared to other restoration and conservation strategies, the approaches are incredibly cheap and they can produce and sustain dynamic biophysical processes that are thought to be so important to sustaining healthy heterogeneous stream habitat. However, with those dynamics comes the potential for misguided and unrealistic management expectations. Not all streams can support high levels of beaver dam activity and in certain contexts their engineering activities are a nuisance and in direct conflict with other management priorities. So where are good places to employ beaver as a restoration agent and promote their dam building activities? Given the limitations of existing beaver habitat suitability models there is a critical need to develop and implement reliable models for assessing where encouraging beaver may be an appropriate restoration priority.

Although beaver can survive under a huge range of conditions (e.g., found everywhere from Boreal forests to desert canyonlands like the mainstem Colorado River in the Grand Canyon), from a stream and river restoration perspective, the ecosystem benefits they provide are primarily through their dam building activities. They generally do not dam large mainstem rivers, but instead borough in banks and/or dam side-channels and modify floodplain habitats. Thus, we focus in this study on the development of a beaver-dam capacity model approach. Beaver dams, not beaver themselves, provide the restoration outcomes we seek. Thus, it seems appropriate to gauge a riverscape's capacity to support dam-building beaver rather than the suitability of the landscape to support beaver. With such a capacity approach, resource managers would have the information necessary to determine where and at what level re-introduction of beaver and/or conservation is appropriate and what the likely outcomes might be in terms of restoration. However, such an approach on its own is not enough due to land use practices that can seriously limit the capacity of landscape to support dam-building beaver. In a western US context, one of the most important among these limiting factors is ungulate grazing pressure in riparian zones and must be assessed in order to consider the extent to which such pressures limit the landscape's capacity to support dam-building beaver.

Several studies have shown that grazing by domestic ungulates is a major factor in the decline of riparian plant communities (Belsky and Uselman, 1999; Case and Kauffman, 1997; Fleischner, 1994; Kauffman et al., 1983). In addition, Beschta (2003) suggests that heavy grazing, by domestic or wild ungulates, is a major factor limiting landscapes from reaching their beaver potential because ungulate herbivore is particularly damaging to aspen and cottonwood establishment since these seedlings and saplings are highly palatable (Braatne et al., 1996; Clayton, 1996; Heilman, 1996; Whitham, 1996). This is supported by Baker et al. (2005) who found that reintroductions of beaver often fail in riparian environments that are heavily browsed by livestock or ungulates (see also McColley et al., 2011). In this pilot study, we experiment with the preliminary development of an ungulate capacity model that will provide spatially explicit information regarding grazing capacity.

An ungulate model can eventually be combined with the beaver dam capacity model to build a tool to assess beaver restoration potential (BRAT – Beaver Restoration Assessment Tool). To maximize the effectiveness of such a tool it must be designed to be easily transferable to other watersheds. This could be achieved through the use of freely and widely (e.g., nationally) available GIS data as model inputs. Therefore, the primary objective of this pilot research project was to demonstrate that it is possible to develop a cost-effective, rapid, desktop GIS beaver habitat assessment model, which could be used as a restoration, conservation and climate change adaptation planning tool. Specifically, we used readily available nation-wide GIS data to:

1. Develop a model to assess the capacity of riverscapes to support dam-building beaver;
2. Test this capacity model in a case study application, Escalante River watershed
3. Develop a preliminary ungulate capacity model and examine areas where heavy grazing and beaver dam building capacity intersect.

STUDY AREA

A case study application was carried out in the Escalante River watershed (watershed; 37°48’ N, 111°32’ W) located in southern Utah, USA. The watershed was an ideal location for the pilot/proof of concept study for a number of reasons:

1. In 2010, the State of Utah developed their first Beaver Management Plan. An important component of the plan was to identify areas of potential beaver reintroduction to restore degraded watersheds and one of the candidate watersheds was the Escalante.
2. The watershed’s location, at the southern extent of the beaver distribution, has a diverse range of habitats ranging from alpine meadow to desert southwest slot canyons. These represent a range of conditions from where neither water nor wood is limiting to situations where both are limiting and make an ideal test bed for identifying beaver dam-building capacity thresholds across a physiographically diverse landscape.
3. Detailed ground-based surveys of the watershed (GCT data, 2010-2011) compared with known areas of historic beaver activity suggest that beaver are currently occupying far fewer sites at much lower densities. In addition, high intensity livestock grazing and expanding elk herds are likely depleting many aspen, cottonwood and willow riparian habitats. This apparent decline in woody riparian vegetation may be limiting beaver populations.
4. The watershed supports some of the last major stands of endangered Gooddings Willow-Fremont Cottonwood gallery forest on the Colorado Plateau, and contains five native fish species, three of which are protected through a conservation agreement with the State of Utah. It is, therefore, precisely the type of watershed in which beaver are a prime candidate for restoration and conservation work.

The watershed is 5,244 km^2 in size and the vast majority (97%) is public lands, managed by Grand Staircase-Escalante National Monument (Bureau of Land Management), Dixie National Forest (US Forest Service) and Glen Canyon National Recreation Area (National Park Service) (Figure 2). Small parcels of private and state lands occur, especially near the towns of Escalante and Boulder, the only two towns located in the watershed.

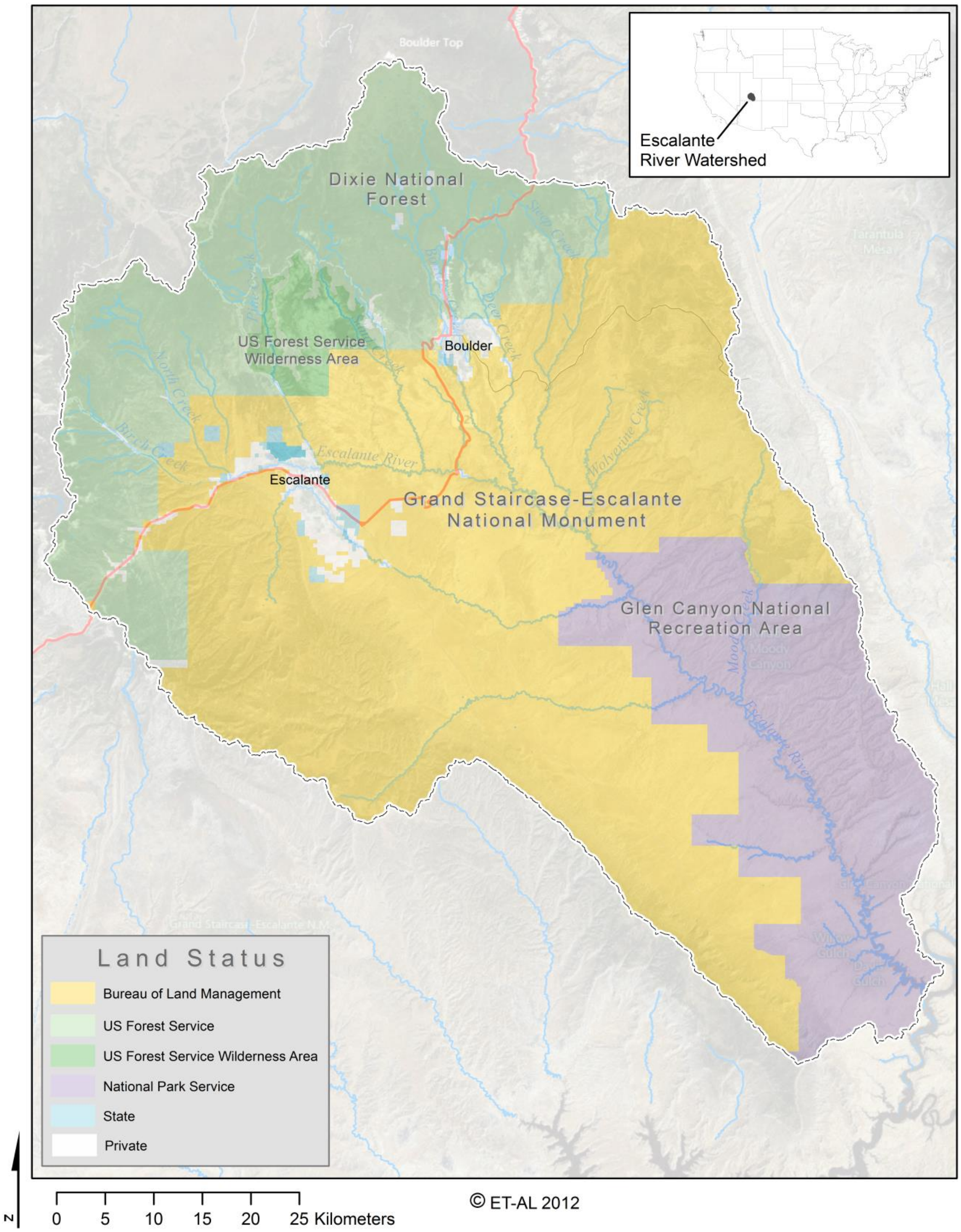


Figure 2 - Escalante River watershed showing land status and ownership.

TOPOGRAPHY AND CLIMATE

The watershed has a vertical relief of 2,287 meters with the highest elevation of 3,415 m on the rim of the Aquarius Plateau (Boulder Mountain) and the lowest elevation of 1,128 m at the inflow of the Escalante River into Lake Powell. The watershed's wide range of elevation results in wide-ranging gradients in temperature and precipitation that forms three climate zones: upland, semi-desert, and desert. In the upland zone, temperatures are cold in winter and mild the remainder of the year and precipitation falls primarily as snow in winter. In the semi-desert and desert zones the majority of precipitation occurs during a summer monsoon season from July to September in the form of thunderstorms with summer temperatures regularly exceeding 38 degrees C (Christensen and Bauer, 2005). Annual precipitation in the watershed varies from approximately up to 635mm at the highest elevations to about 150 mm at the lowest elevations (Christensen and Bauer, 2005).

ECOREGIONS

The dramatic vertical relief of the watershed also forms four distinct level IV Ecoregions: High Plateaus, Escarpments, Semiarid Benchland/Canyonlands and Arid Canyonlands (Woods et al., 2001; Figure 2). The only portion of the watershed considered part of the High Plateaus Ecoregion is the Aquarius Plateau, a high elevation mountain top consisting of flat to rolling topography characterized by mostly dwarf coniferous forests. The Escarpments Ecoregion consists of basalt cliff bands that descend dramatically from the forested plateau rim. Below the escarpment of Boulder Mountain there is a broad expanse of less steep terrain that contains quaking aspen (*Populus tremuloides*) forests scattered with wet meadows dominated by grasses and forbs, numerous ponds, lakes and headwater streams. The riparian areas, where healthy, consist of native woody riparian vegetation including, narrowleaf cottonwood (*Populus angustifolia*), bigtooth maple (*Acer grandidentatum*), Rocky Mountain maple (*Acer glabrum*), water birch (*Betula occidentalis*), aspen (*Populus tremuloides*), thin-leaf alder (*Alnus tenuifolia*), and willow (*Salix spps*) (Woods et al., 2001). Even though this is a distinct landscape unit at the coarse scale of 1:1,175,000 (the scale of the ecoregion mapping) this transition zone is mapped as part of the Escarpments Ecoregion. This area is prime habitat for dam-building beaver. Below this relatively lush zone are the Semiarid Benchlands that are characterized by a mosaic of grassland, shrubland, and woodland-covered benches that support saltbush (A*triplex canescens*), sagebrush (*Artemisia spps*) and pinyon (*Pinus edulis*) /juniper (*Juniperus osteosperma*) depending on aspect and elevation (Woods et al., 2001). The Arid Canyonlands ecoregion is dominated by sandstone canyons, mesas and outcroppings and blackbrush (*Coleogyne ramosissima*), shadscale (*Atriplex confertifolia*), and drought tolerant grasses dominate (Christensen and Bauer, 2005; Woods et al., 2001).

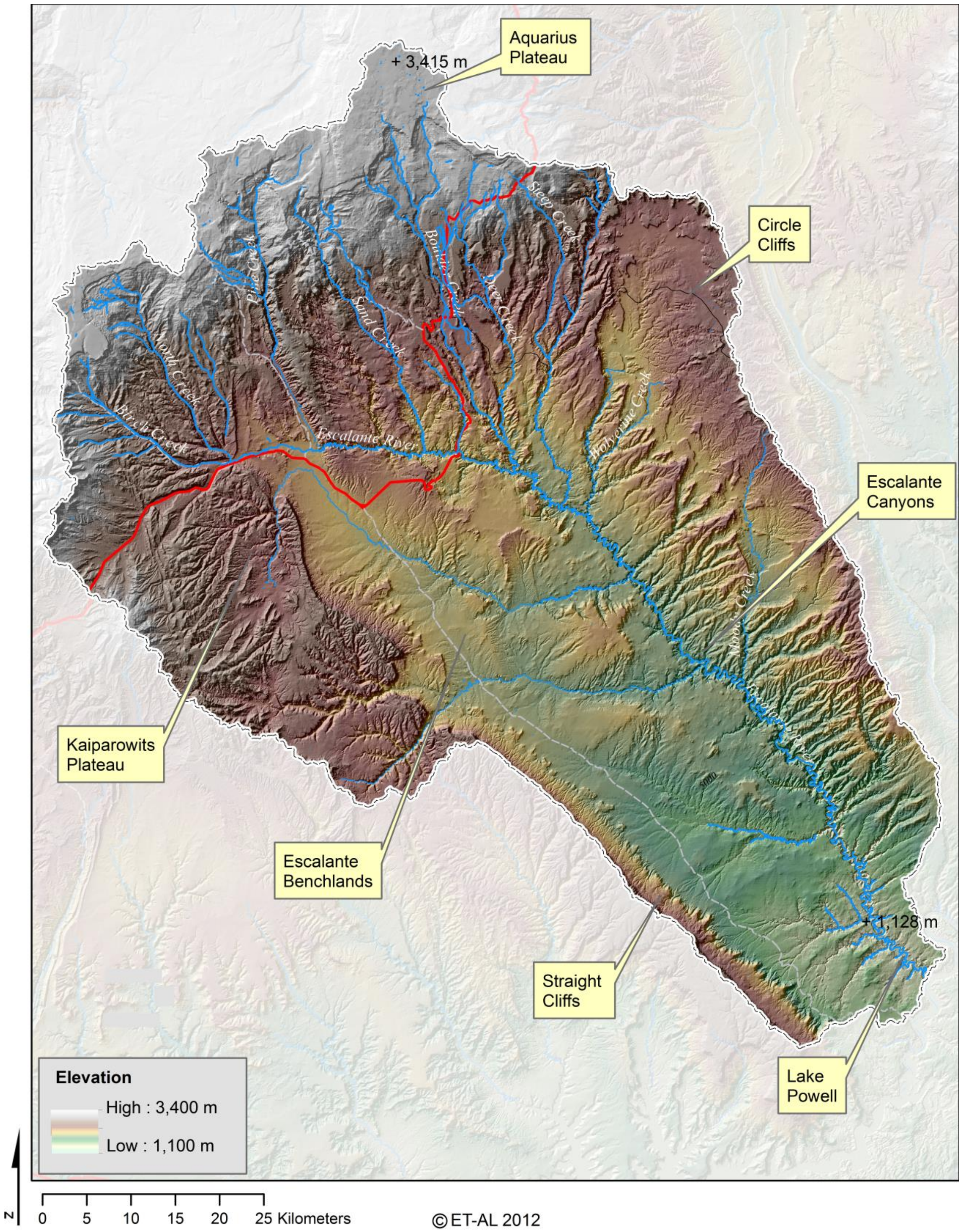


Figure 3 - Escalante River watershed showing topography and place names.

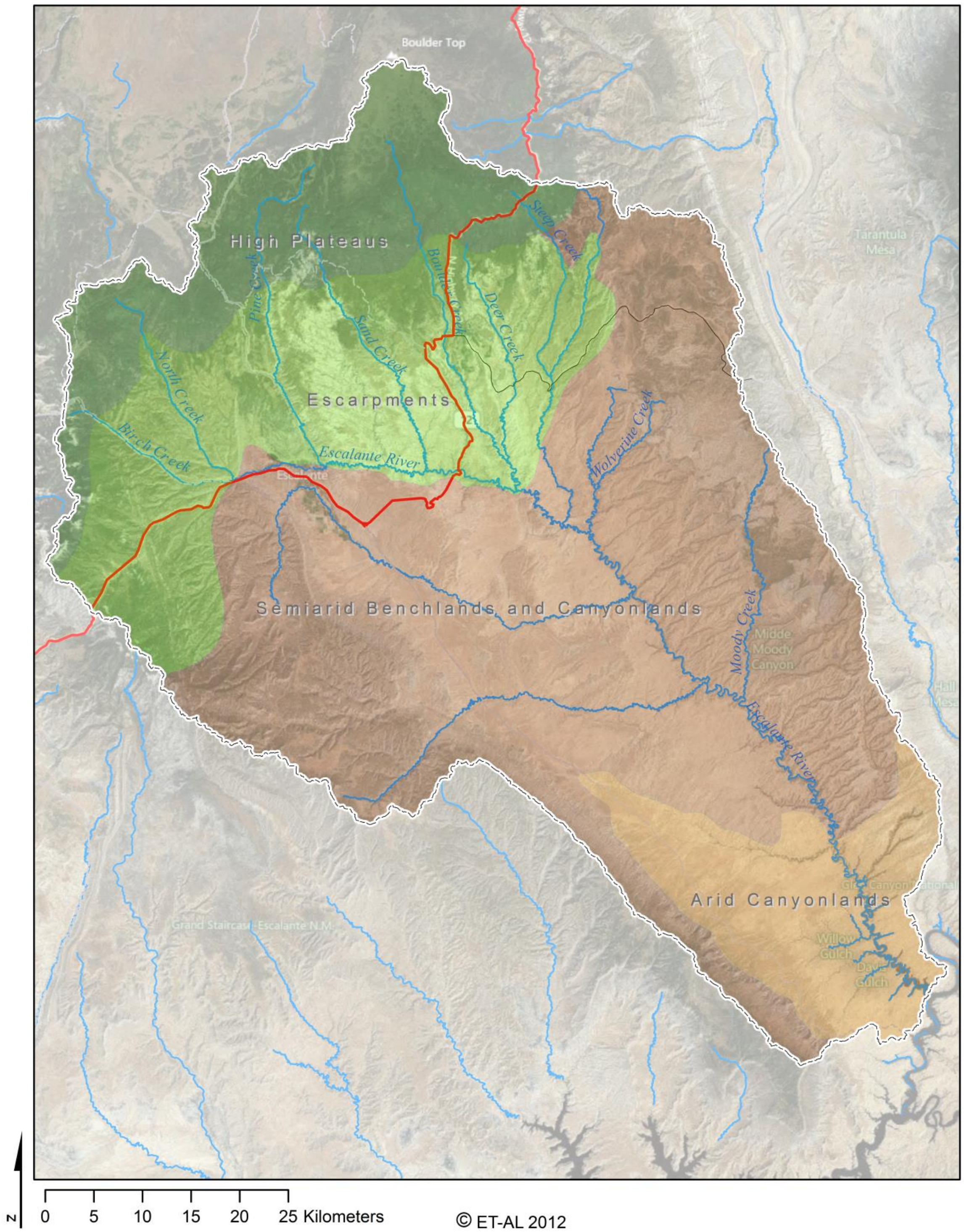


Figure 4 - Escalante River watershed showing Ecoregions (Woods et al., 2001) and topography.

Figure 5 - Oblique Aerial photo (May 28, 2012) of Boulder Mountain showing the conifer dominated mountain top and escarpment and the conifer/aspen and mountain meadows below.

Figure 6 - Oblique aerial photo (May, 27, 2012) showing the maze of twisting sandstone canyons found in the lower portion of the Escalante River watershed.

The riparian areas in the headwater canyons and along the Escalante River are dominated by native willows and cottonwood, but also contain box elder (*Acer negundo*) and in some areas are dominated by invasive tamarisk (*Tamarix spp.*) and Russian olive (*Elaeagnus angustifolia*) (Christensen and Bauer, 2005). Control of exotic plants including tamarisk and Russian olive, and restoration of cottonwood trees is underway by the Escalante River Watershed Partnership (Figure 7).

Figure 7 - Oblique aerial photo (May 27, 2012) of the Escalante River riparian corridor at the Highway 12 Bridge. This photo documents the invasion of Russian olive in this area. Look for the distractive grey-green leaves of the Russian olive tree.

The Escalante River was once a right-bank tributary to the Colorado River. Today, the Escalante only flows approximately 145 km before joining Lake Powell, which now dams the Colorado River. The Escalante begins northwest of the town of Escalante at the confluence of North Creek and Birch Creek and flows generally southeasterly toward the Colorado River. However, because these upper watershed streams are diverted for irrigation, most of the flow comes from Pine Creek, Death Hollow, Sand Creek, Calf Creek and Boulder Creek. Each of these streams flow off the Aquarius Plateau (Christensen and Bauer, 2005). The majority of the drainage network is comprised of streams indicated as intermittent on 1:24,000 USGS topographic maps and NHD data (Figure 8). Two USGS stream flow gages are located within the watershed, on Pine Creek and Escalante River both near the town of Escalante. The annual hydrograph for the Escalante River shows a snowmelt dominated hydrograph with peak flows typically occurring in May and summer baseflows down to a trickle at 0.28 m^3s^{-1} (Christensen and Bauer, 2005).

Figure 8 - Escalante River watershed showing perennial and intermittent streams as defined by the National Hydrologic Dataset (NHD).

METHODS

Unlike efforts to differentiate habitat suitability on the basis of correlation of readily available or measurable environmental variables (e.g., stream slope) to where beaver are found (e.g., Allen, 1983), we focused our modeling efforts here specifically on potential beaver dam building activity. Beaver are highly adaptable generalist herbivores that can survive foraging on a wide variety of plant materials ranging from hardwoods to, grasses, herbs and even row crops (Allen, 1983). Beaver do need to regularly chew on wood or something that can wear down their incisors, which grow very rapidly (Müller-Schwarze and Sun, 2003). However, this chewing need can be met by a wide range of woody species. Beaver are very adept swimmers, but are vulnerable to predators when out of the water, so they need deep enough water to swim in and provide protection from predators. In simple terms, they need water and wood and these needs can be met by many different water-bodies including natural ponds, lakes, rivers and perennial streams. Their dam-building behavior is only exercised in environments (e.g., lower order streams or side channels of major rivers), where the habitat does not provide them with adequate cover or deep enough water to maintain underwater entrances to their lodges and/or store winter food caches in areas where the stream may freeze over in the winter. Unlike the extremely wide range of environments which can support beaver foraging, colonization and/or migration, where beaver build dams is a much narrower range of environments tied to explicit functional needs. Moreover, from a restoration and conservation perspective, it is the dam-building activity that is the ecosystem engineering that provides the positive feedbacks we are most interested in.

At any given point in time and space, actual beaver dam densities will be a function of many complex spatial and historical contingencies. Paramount amongst these are the availability of wood and water resources as well as potential physical disturbances (e.g., floods). An area that is not currently utilized one year and is at 0% capacity may be at 100% of capacity the next year simply because a dispersing beaver or a colony moved into that area. These fluctuations are an important part of the diversity, discontinuities and dynamics of beaver dam influenced systems (Burchsted et al., 2010), and are not something we are attempting to model explicitly. The model we developed attempts to approximate capacity numbers on a drainage network in terms of the number of dams per kilometer. We define capacity as the maximum number of dams the local riverscape can support, on average through time. In a system where wood and water resources are not limiting (e.g., boreal forests), most places in a riverscape might have equally high capacities (e.g., upwards of 25-40 dams/km). However, in a system where either wood and/or water resources are limiting (e.g., semi-arid or arid western streams), capacity may vary greatly in accordance with resource availability and disturbance potential. Conceptually, we might imagine capacity for many western US systems as the number of dams per kilometer one would have mapped had they visited these systems prior to European trapping and settlement.

The reasons we chose to model dams per kilometer are because a) it is something that is directly comparable to measurements that can be made on the ground with simple mapping, b) it can often be approximated aerially with good aerial imagery and/or overflights, and c) it is commonly reported in the literature so there are good numbers for comparison. Although many past investigators and beaver monitoring programs attempt to infer the number of colonies and rough population estimates of beaver from a simple count of the number of dams (e.g., citations), the accuracy of such methods are very poor.

To model capacity to support dam building activity by beaver we used a combination of simple GIS spatial models and fuzzy inference systems (FIS). Traditional habitat suitability models struggle from the challenge of how to combine different pieces of empirical evidence, typically in the form of correlations between where we observe species utilizing habitat to some physical measure of that habitat. The bigger challenge is in our inferences of how utilization patterns might translate to suitability or even preferences (Leclerc, 2005a; Leclerc, 2005b). By contrast, fuzzy inference systems allow 'computing with words', whereby multiple lines of evidence can be combined mathematically with simple rule tables and the uncertainty arising from ambiguity in categorical data is explicitly accounted for (Openshaw, 1996; Zadeh, 1996). Moreover, fuzzy habitat models are much more flexible and easy to apply without invalidating necessary assumptions of traditional habitat models (Schneider and Jorde, 2003).

Our estimates of beaver dam densities at full capacity came from the following lines of evidence:

1. Evidence of a perennial water source
2. Evidence of riparian vegetation to support dam building activity
3. Evidence of adjacent vegetation (on riparian/upland fringe) that could support expansion and establishment of larger colonies
4. Evidence that a beaver dam could physically be built across the channel during low flows
5. Evidence that a beaver dam is likely to withstand typical floods

We formulated a capacity model that should perform well if accurate evidence is used as an input. However, we were primarily interested in developing a tool that could be run across broad geographic regions (e.g., entire watersheds, states, land management units) based on readily available lines of evidence and which would give a reasonable, better than first-order approximation. Below, we discuss where we acquired data sources and how we prepped, processed and analyzed each piece of evidence as well as how we combined them into a prediction of maximum beaver dam density. The theoretical justification for the models and underlying methods are described here, whereas full documentation of the data sources required and geoprocessing steps needed to run the model manually are available at http://brat.joewheaton.org.

BEAVER DAM CAPACITY MODEL

Our beaver dam capacity model used the National Hydrologic Dataset Plus (NHD*Plus*) as the baseline drainage network on which beaver dam capacity would be modeled (McKay et al., 2012). The NHD*Plus* network layer is already broken into segments between confluences and diffluence junctions. We further segmented the network into 250 m long segments over which all our modeling analyses would be based (Figure 8). We chose 250 m segments partly because i) this was a reasonable length over which to approximate reach-averaged slope using coarse 10 m resolution digital elevation models (DEMs) from National Elevation Dataset (USGS, 1999), and ii) this should produce a reasonable sample of riparian vegetation conditions in the vicinity of a reach from 30 m LANDFIRE data. The first step was to download and clip the NHD*Plus* dataset down to the watershed of interest.

EVIDENCE OF PERENNIAL WATER SOURCE

Although intermittent streams in close proximity to a reliable spring or not too far from a perennial stream are occasionally used by beaver (Hood and Bayley, 2008a; Hood, 2011), the vast majority of their lengths are never used by beaver because of the unreliability of the water source. Intermittent streams were eliminated as a model input based on research that states that beaver require a permanent, relatively constant water flow (Allen, 1983; Buech, 1985; Williams, 1965). The NHD perennial stream network (Figure 8) for the watershed was divided into 250 m segments (stream reach) and this became the minimum mapping unit for this project. The NHD data processing consisted of four straightforward GIS processing steps:

1. The NHD stream layer was subset to perennial streams;

2. The perennial streams were segmented to 250 m lengths;

3. The segmented streams (250 m lengths) were buffered by 30 m width, and

4: The segmented streams (250 m lengths) were also buffered 100 m width

EVIDENCE OF WOOD FOR BUILDING MATERIAL

To assess the evidence of wood availability for dam building, we used the nationwide LANDFIRE vegetation dataset, which is based on classification of 30 m resolution LANDSAT satellite imagery. LANDFIRE (2013) land cover data of both existing (from 2008) and potential vegetation was classified according to beaver preferences established in the literature. We assigned a single numeric suitability value from 0 and 4, with 0 representing unsuitable food/building material and 4 representing preferred food/building material to each of the land cover classes (Figure 9).

Beaver are generalist herbivores that eat the leaves, twigs and bark of woody plants as well as aquatic and terrestrial herbaceous vegetation (Allen, 1983). An adequate and accessible supply of food/dam building material must be available for the establishment and persistence of a dam-building beaver colony (Slough and Sadleir, 1977). Total biomass of woody plants used for winter food caches likely limits potential of an area rather than total biomass of herbaceous vegetation (Boyce, 1981). Williams (1965) reported that suitable habitats for beaver must contain quality food species present in sufficient quantity. Furthermore, Denney (1952) investigated woody plant preferences of beaver throughout North America and found strong preferences for particular plant species, in order of preference, beaver selected aspen (Populus tremuloides), willow (Salix spp.), cottonwood (P. balsamifer), and alder (Alnus spp.).

The classification model shown in Figure 9 is a simple look-up table and can be applied spatially to either vector or raster data on a feature-by-feature basis or a cell-by-cell basis respectively. The vegetation data we used was the raster LANDFIRE land cover data at 30 m pixel resolution. Thus, each pixel was given a dam-building capacity rating of (0-4) as shown going from 1 to 2 in Figure 10.

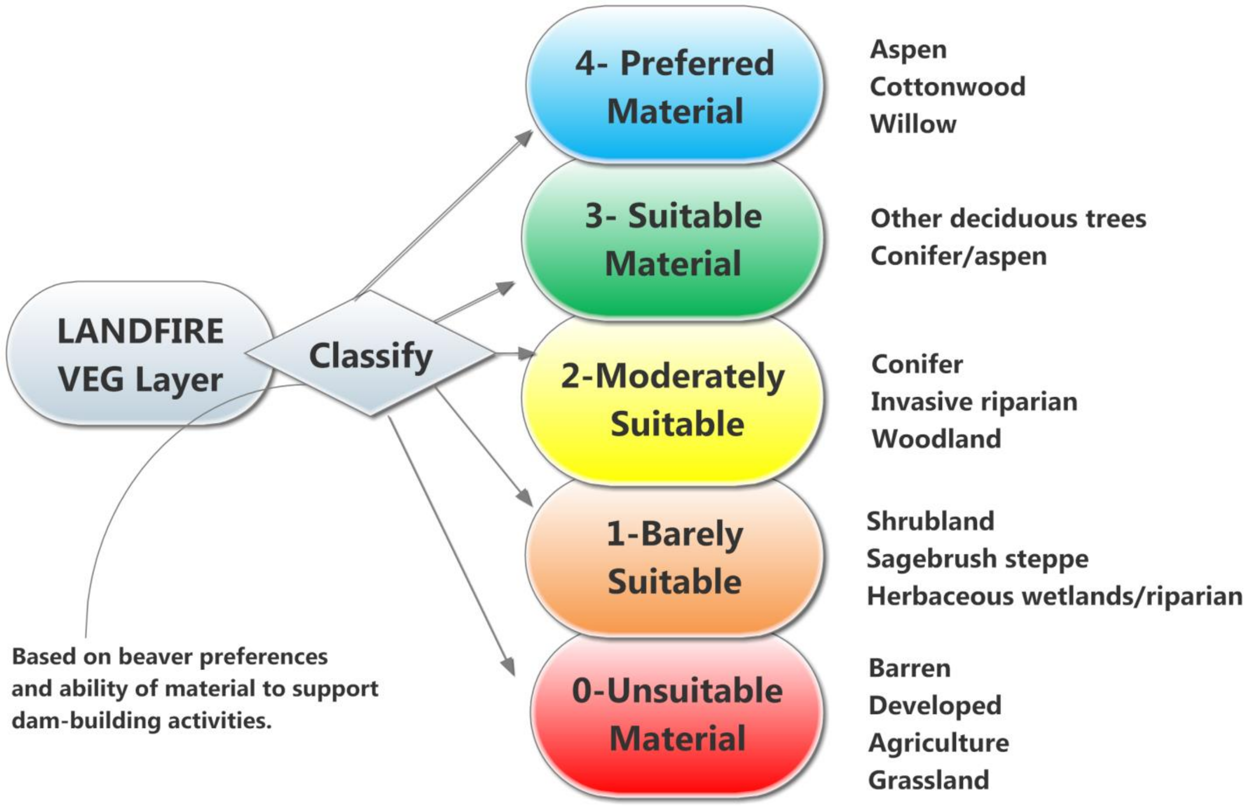


Figure 9 - Suitability of vegetation (from LANDFIRE) as a beaver dam building material.

While the classified suitability map is useful, for beaver we really are only concerned with that portion of the map within the foraging and harvesting range of beaver from perennial water sources. However, there is a major contrast in riverscapes that have suitable vegetation in a narrow band within or along their banks, versus those that have expansive riparian or upland forests with desirable woody forage and building materials. For example, an incised channel with an inset bench boasting preferred willows all along it can support some beaver dam building activity, but large dam complexes supporting stable colonies require a larger supply of suitable and preferred woody building materials within the surrounding vicinity. To represent this important contrast, we derived two buffers along our perennial drainage network:

- A 30 m buffer representing just that vegetation available in and along the banks of the stream or river (Figure 10- see step 3a); and
- A 100 m buffer representing that vegetation within a broader riparian and/or upland buffer that would be available to beaver for harvest and hauling back to the water (Figure 10- see step 3b).

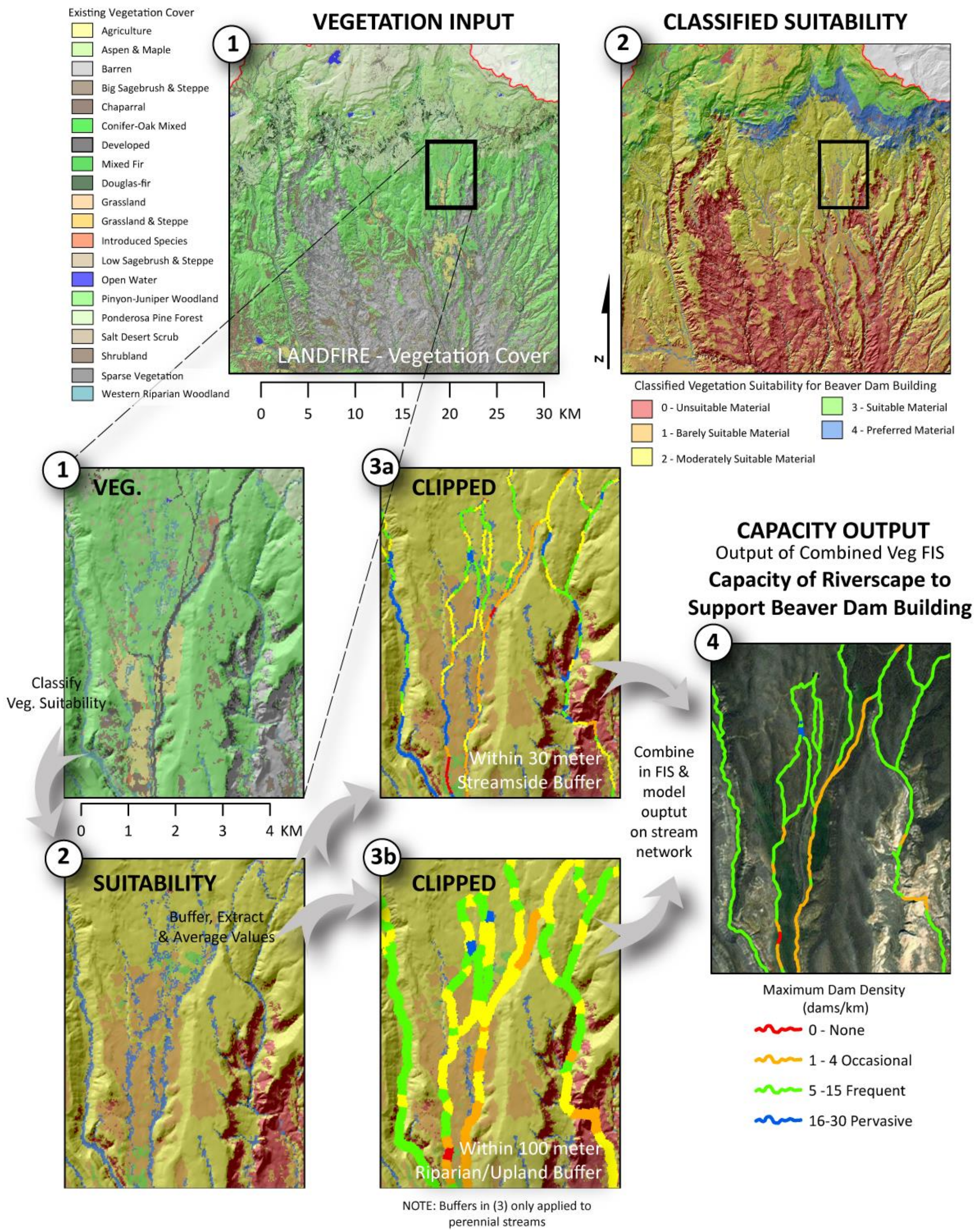


Figure 10 – Illustration of workflow for determining capacity of riverscape to support beaver dam building activity, based solely on availability of suitable building materials. The top rows show the broad spatial availability of vegetation data (1), and how it can be classified (2) using the rules in Figure 8. These suitability classes are then averaged within two buffers: a streamside buffer in 3a and a riparian/upland buffer in 3b. They are then combined using a fuzzy inference system to produce a maximum dam density capacity model (4).

The buffer distances were based on the following: Jenkins (1980) found that most of the woody species utilized by beaver were within 30 m of the edge of water. However, some foraging did extend up to 100 m. Likewise, Hall (1970) reported that 90 percent of all cutting by beaver of woody material was within 30 m of the pond edge. Similarly, Barnes and Mallik (2001) and Schwab (2002) found that beavers concentrated their herbivory to within 20m of the pond edge. While Allen (1983) considered a 200 m forage buffer, he conceded that a majority of foraging occurs within 100 m. As we were interested in wood as a building material for dam construction, there is much less evidence for wood that is actually used in dam construction being harvested much farther away than 100 m. We assumed that where wood was available in this zone as a building material, food availability would not be limiting.

While simply buffering the stream network provides an area within which we can clip the raster suitability model (Figure 10- see step 2), we still have a distribution of suitability categories within each buffered polygon segment. To convert this distribution of categorical values (i.e., 0s, 1s, 2s, 3s and 4s) to a continuous input that can be assigned to each buffer segment, we used a zonal statistics geoprocessing operation that calculates the mean of all categorical values for food/building materials. This calculation was done for both the 30 m and 100 m buffers. Although Figure 10 (steps 3a and 3b) are symbolized to show a categorized output for each of these mean vegetation scores for each buffered stream segment, they are actually continuous values. These values are then extracted from the polygon buffers and mapped onto the polyline drainage network for each segment. Thus, two new fields end up in the attribute table of the NHD drainage network: a riparian vegetation score and an adjacent vegetation score.

Next, these two lines of evidence about availability of building materials are combined to estimate collectively how much dam building activity the riverscape can support (in terms of dam density). To do this, we use a fuzzy inference system that allows us to develop a linguistic expert-based rule system (Table 1), but relies on continuous numeric input variables and a continuous output (Adriaenssens et al., 2003; Klir and Yuan, 1995). The Fuzzy Logic Toolbox 2.0 in Matlab was used to run the model (Jang and Gulley, 2009). The rule table developed is shown in Table 1 and the specification of membership functions for the linguistic categories for inputs and the output is shown in Figure 11. Note that the input membership functions are centered on the categorical values (1, 2, 3 and 4) used in vegetation classification of Figure 9. By contrast, the output membership function is calibrated to values typically reported in the literature and that we have documented throughout the West: for none (0), occasional (0-5 dams/km), frequent (4-25 dams/km) and pervasive (12-40 dams/km). This model is applied on each polyline stream segment and the output is an aggregated membership function that represents the full range of uncertainty in predicting the 'capacity' in dams per kilometer. That output membership function is defuzzified using its centroid, so that a crisp output in dams per kilometer can be reported and used for symbolizing the drainage network (e.g., step 4 in Figure 10). This output is an intermediate output, and is only based on the availability of building materials. It does not consider the extent to which other factors may limit beaver from achieving this capacity (e.g., floods).

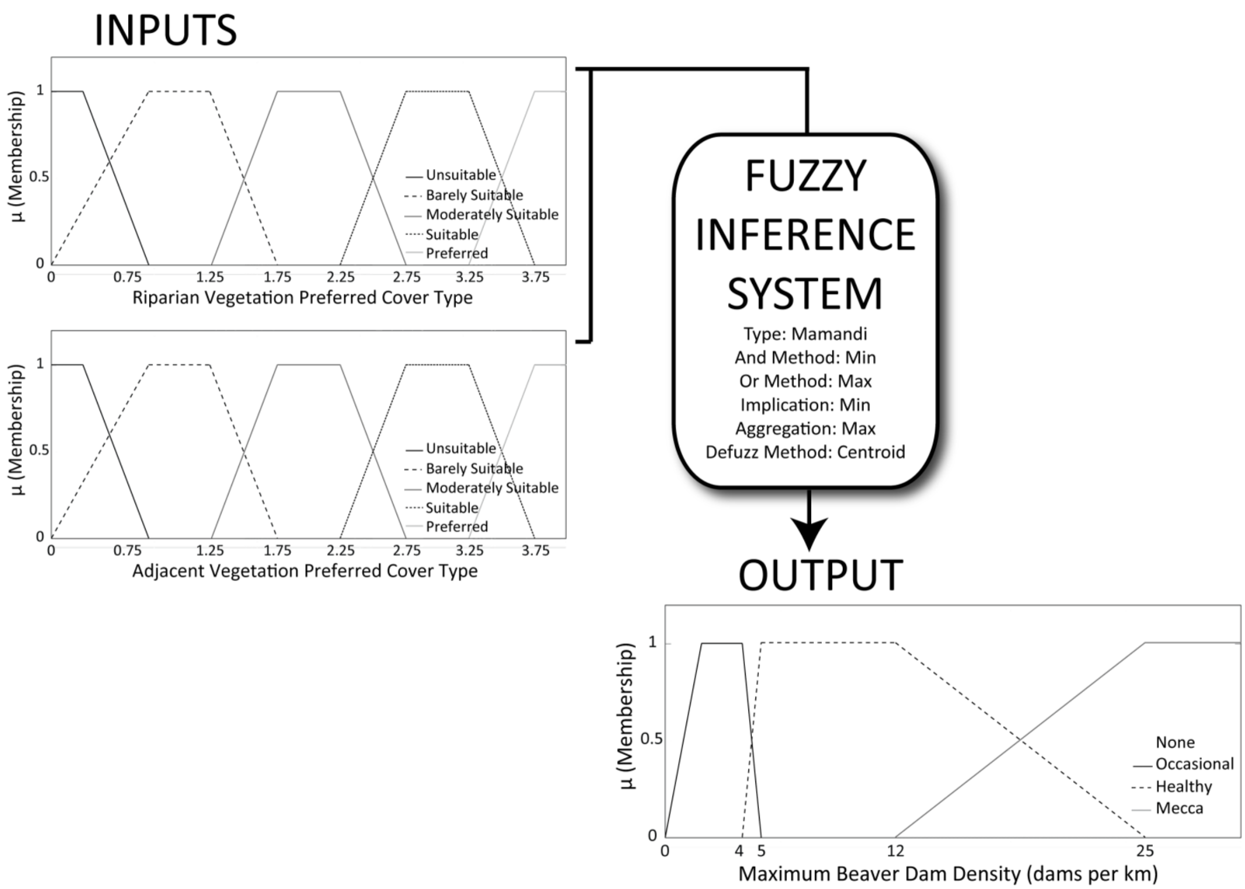


Figure 11 - Fuzzy Inference System for capacity of riverscape to support dam building beaver activity based ONLY on vegetation available as a building material. This shows the specification of fuzzy membership functions with overlapping values for categorical descriptors in inputs and the output.

Table 1 – Rule table for two input fuzzy inference system that models the capacity of the riverscape to support dam building activity (in dam density) using the suitability of streamside vegetation and suitability of riparian/upland vegetation as inputs.

	INPUTS					OUTPUT
	IF	Suitability of Streamside Vegetation		Suitability of Riparian/Upland Vegetation		Dam Density Capacity
RULES	1	Unsuitable	&	Unsuitable	, then	None
	2	Barely Suitable	&	Unsuitable	, then	Occasional
	3	Moderately Suitable	&	Unsuitable	, then	Occasional
	4	Suitable	&	Unsuitable	, then	Occasional
	5	Preferred	&	Unsuitable	, then	Frequent
	6	Unsuitable	&	Barely Suitable	, then	Occasional
	7	Barely Suitable	&	Barely Suitable	, then	Occasional
	8	Moderately Suitable	&	Barely Suitable	, then	Occasional
	9	Suitable	&	Barely Suitable	, then	Frequent
	10	Preferred	&	Barely Suitable	, then	Frequent
	11	Unsuitable	&	Moderately Suitable	, then	Occasional
	12	Barely Suitable	&	Moderately Suitable	, then	Occasional
	13	Moderately Suitable	&	Moderately Suitable	, then	Frequent
	14	Suitable	&	Moderately Suitable	, then	Frequent
	15	Preferred	&	Moderately Suitable	, then	Frequent
	16	Unsuitable	&	Suitable	, then	Occasional
	17	Barely Suitable	&	Suitable	, then	Occasional
	18	Moderately Suitable	&	Suitable	, then	Frequent
	19	Suitable	&	Suitable	, then	Frequent
	20	Preferred	&	Suitable	, then	Frequent
	21	Unsuitable	&	Preferred	, then	Occasional
	22	Barely Suitable	&	Preferred	, then	Frequent
	23	Moderately Suitable	&	Preferred	, then	Frequent
	24	Suitable	&	Preferred	, then	Pervasive
	25	Preferred	&	Preferred	, then	Pervasive

ROLE OF STREAM POWER

There are many rivers and streams where beaver cannot build dams, even at baseflows. For example, beavers cannot build dams across the mainstem Colorado River in the Grand Canyon, nor can they build dams in really steep mountain streams and creeks with baseflows that are simply too powerful for them to even get a start. There are other places where they may build a dam at baseflow, but every flood blows it out (Demmer and Beschta, 2008). Previous investigators have frequently attempted to represent this observation by correlating beaver occupancy and/or beaver dams to stream slope (Allen, 1983; Barnes and Mallik, 1997). From a spatial modeling perspective, using slope is desirable because stream slopes can be easily measured in the field and simply derived from readily available digital elevation models for any stream segment of reasonable length (e.g., > 100m). Unfortunately, beaver frequently defy these simple slope correlations and build dams in very steep streams (e.g., up to 15% slopes) despite the conventional wisdom conveyed in the beaver literature.

While slope is an important input in determining the forces a beaver dam may be subjected to, it is not a direct measure of those forces. Moreover, because of the vast variation beaver employ in the building materials they use, how they construct their dams, and the flow conditions dams are subjected to, a simplistic force-balance approach is not tractable for the simple reason that estimating the resisting forces of the dam itself is an impenetrable exercise. Although not perfect, stream power gives a simple and well understood proxy for the flow strength within any given stream segment (Worthy, 2005) that is the product of slope (S) and discharge (Q):

$$\Omega = \rho \cdot g \cdot Q \cdot S$$

Where Ω is total stream power, ρ is the density of water (1000 kg/m^3), g is acceleration due to gravity (9.8 m/s^2), Q is discharge (m^3/s), and S is the channel slope. Stream power (Ω) is readily calculable for any segment of stream if Q is known, because S can be derived from a DEM and drainage network and the density of water (ρ) and gravity (g) are constants. An estimate of Q can be obtained from direct measurement or distributed hydrologic modeling, both of which are too labor intensive to do over large regions in the context of BRAT. A simple estimate of Q can be achieved by using or deriving regional curve regression equations, which relate Q (at some recurrence interval) to readily calculable values at a site (like upstream drainage area and occasionally elevation). These relations are developed by developing correlations between discharge measurements at gage stations to drainage area. In this pilot study, we relied on USGS publications (Kenney, 2008; Wilkowske et al., 2008) for the state of Utah that developed these regional curves and used the curves directly. Upslope drainage areas were derived for each stream segment directly from 10 m USGS digital elevation models using a cumulative drainage area geoprocessing algorithm.

EVIDENCE THAT A BEAVER DAM CAN BE BUILT

To infer whether or not it was likely that a beaver dam could be built, we calculated stream power at baseflows. Using Wilkowske et al. (2008) for region 6, we approximated baseflow with the discharge exceeded 80% of the time for September (Q_{p80}) following the summer monsoons:

$$Q_{p80} = 9.4102^{-2} \cdot A^{0.7404}$$

Where A is drainage area in square kilometers. This Q_{p80} estimate is then substituted into the stream power equation and used to infer the following simple linguistic categories (Figure 12):

- Can Build Dam
- Can Probably Build Dam
- Cannot Build Dam

Fuzzy membership functions were derived for these categories based on a synthesis of presence and absence data from over 500 dam locations overlaid on baseflow stream power drainage networks for the Bear River Range and over 800 km of perennial streams in the Escalante drainage network. Distributions of stream power were derived for parts of the drainage network that had vegetation suitable to support beaver, but have no evidence for beaver dams ever existing were used for the 'cannot build dam' category. By contrast, stream power distributions derived for areas where beaver were frequently recorded successfully constructing dams were recorded in the 'can build dam' category. Those segments with only occasional (e.g., dispersing beaver) dam activity were used to calibrate the 'can probably build dam' category. The overlap in the stream power distributions were used to represent the overlap in the fuzzy membership functions in the baseflow stream power input of Figure 12.

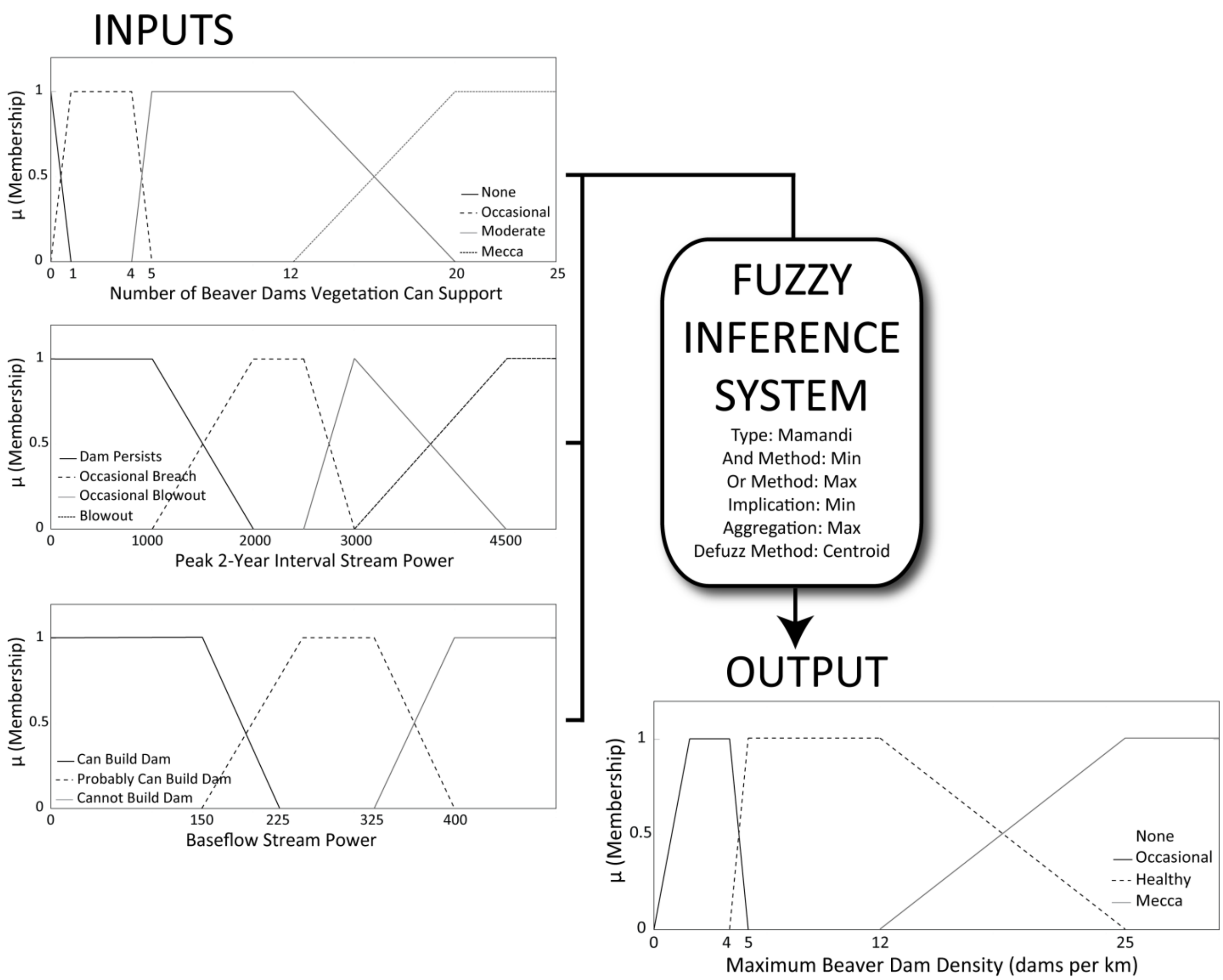


Figure 12 – Fuzzy Inference System for capacity of riverscape to support dam building beaver activity. This shows the specification of fuzzy membership functions with overlapping values for categorical descriptors in inputs and the output.

EVIDENCE THAT A BEAVER DAM WILL LIKELY PERSIST

To infer whether or not it was likely that a beaver dam would persist once built, we calculated stream power at two year recurrence interval flows. Using Ries et al. (2005) for Region 6, we approximated the two year recurrence interval peak flood (Q_2) as:

$$Q_2 = 4150\ A^{0.553} \cdot (El/1000)^{2.45}$$

where A is drainage area in square kilometers and El is elevation. This Q_2 estimate is then substituted into the stream power equation and used to infer the following simple linguistic categories (Figure 12):

- Dam Persists – *regardless of peak flow, the dam remains intact*
- Occasional Breach of Dam – *peak flows may cause a partial breach of a dam that is easily repaired by beaver*
- Occasional Blowout of Dam – *peak flows may occasionally cause a dam to completely wash out, and abandoned, but the frequency of this occurrence is low*
- Blowout – *peak flows will certainly lead to a blowout*

Fuzzy membership functions were derived for these categories based on a synthesis of dam persistence data from over 500 dam locations overlaid on baseflow stream power drainage networks for the Bear River Range and over 800 km of perennial streams in the Escalante drainage network as well as data from Bridge Creek in Oregon and Demmer and Beschta (2008). Distributions of stream power were derived for each of the above categories. The overlap in the stream power distributions was used to represent the overlap in the fuzzy membership functions in the baseflow stream power input of the peak 2-year interval stream power in Figure 12.

COMBINED MODEL

Using all the above described lines of evidence (perennial water source, wood for building materials, evidence they can build a dam, and evidence regarding persistence of dam) we sought to develop a combined model that predicts the capacity of the riverscape to support beaver dam building activity. This combined model estimates maximum beaver dam density (dams per kilometer) that is the result of the above described geoprocessing steps and fuzzy inference systems. Here, one last fuzzy inference system was developed to capture and synthesize observations we could make with words, but is difficult to represent adequately in a traditional habitat suitability model.

For example, most beaver experts would probably have no problem with the following statements representing end-member conditions:

- If there are no building materials (i.e., wood), it does not matter what the baseflows or peak flows are, there will not be any dams.
- If the baseflow stream power is too high, it does not matter what building materials are available or what peak flows are, there will not be any dams.
- If a site is bounded by extensive aspen or cottonwood forests, they can build a dam at baseflows, and those dams persist at high flows, pervasive stable colonies and dam complexes will exist.

The first bullet represents rule 1 in Table 2, whereas the second bullet represents rule 2, and the third rule 5. Table 2 represents the combined fuzzy inference system rule table that was developed by expert judgment (with reference to the literature). Figure 12 shows how the three input membership functions were calibrated to revise the prediction of maximum dam density developed in the first model (Figure 11). Figure 13 shows an example of how, when applied spatially, these three inputs can combine to produce an output. In the case of the example shown, the final output is only subtly different from the output of the first model (input 1). These subtle differences represent the few localities in this particular example where stream power was limiting the construction and/or persistence of dams.

Our riverscape capacity model should not be confused with 'carrying capacity' models that estimate the size of a population at equilibrium in the absence of stochasticity (e.g., Ziv, 1998). Our model is not intended to be used to estimate population sizes, though many investigators do attempt to infer population size from the number of dams, active food caches, or inferred colonies around dam complexes. Our model instead estimates the maximum number of dams beaver could build given the resources and physical conditions present (e.g., flows). The maximum dam density our model will produce is 40 dams per kilometer, or roughly a dam every 25 meters, which we do see occasionally. This sort of spacing tends to only persist for short distances around a dam complex, which is typically anywhere from 3 to 15 dams.

Table 2 - Rule table for a three input fuzzy inference system that models the capacity of the riverscape to support dam building activity (in dam density) using the vegetative dam density capacity (output of Table 1 model), baseflow stream power and the 2-year flood stream power.

	IF	INPUTS: Vegetative Dam Density Capacity (FIS)		Baseflow Stream Power		2 Year Flood Stream Power		OUTPUT: Dam Density Capacity
RULES	1	None	&	-	&	-	, then	None
	2	-	&	Cannot Build Dam	&	-	, then	None
	3	Occasional	&	Can Build Dam	&	Dam Persists	, then	Occasional
	4	Frequent	&	Can Build Dam	&	Dam Persists	, then	Frequent
	5	Pervasive	&	Can Build Dam	&	Dam Persists	, then	Pervasive
	6	Occasional	&	Can Build Dam	&	Occasional Breach	, then	Occasional
	7	Frequent	&	Can Build Dam	&	Occasional Breach	, then	Frequent
	8	Pervasive	&	Can Build Dam	&	Occasional Breach	, then	Frequent
	9	Occasional	&	Can Build Dam	&	Occasional Blowout	, then	Occasional
	10	Frequent	&	Can Build Dam	&	Occasional Blowout	, then	Occasional
	11	Pervasive	&	Can Build Dam	&	Occasional Blowout	, then	Frequent
	12	Occasional	&	Can Build Dam	&	Blowout	, then	Occasional
	13	Frequent	&	Can Build Dam	&	Blowout	, then	Occasional
	14	Pervasive	&	Can Build Dam	&	Blowout	, then	Occasional
	15	Occasional	&	Can Probably Build Dam	&	Occasional Breach	, then	Occasional
	16	Frequent	&	Can Probably Build Dam	&	Occasional Breach	, then	Frequent
	17	Pervasive	&	Can Probably Build Dam	&	Occasional Breach	, then	Frequent
	18	Occasional	&	Can Probably Build Dam	&	Occasional Blowout	, then	Occasional
	19	Frequent	&	Can Probably Build Dam	&	Occasional Blowout	, then	Occasional
	20	Pervasive	&	Can Probably Build Dam	&	Occasional Blowout	, then	Frequent
	21	Occasional	&	Can Probably Build Dam	&	Blowout	, then	Occasional
	22	Frequent	&	Can Probably Build Dam	&	Blowout	, then	Occasional
	23	Pervasive	&	Can Probably Build Dam	&	Blowout	, then	Occasional

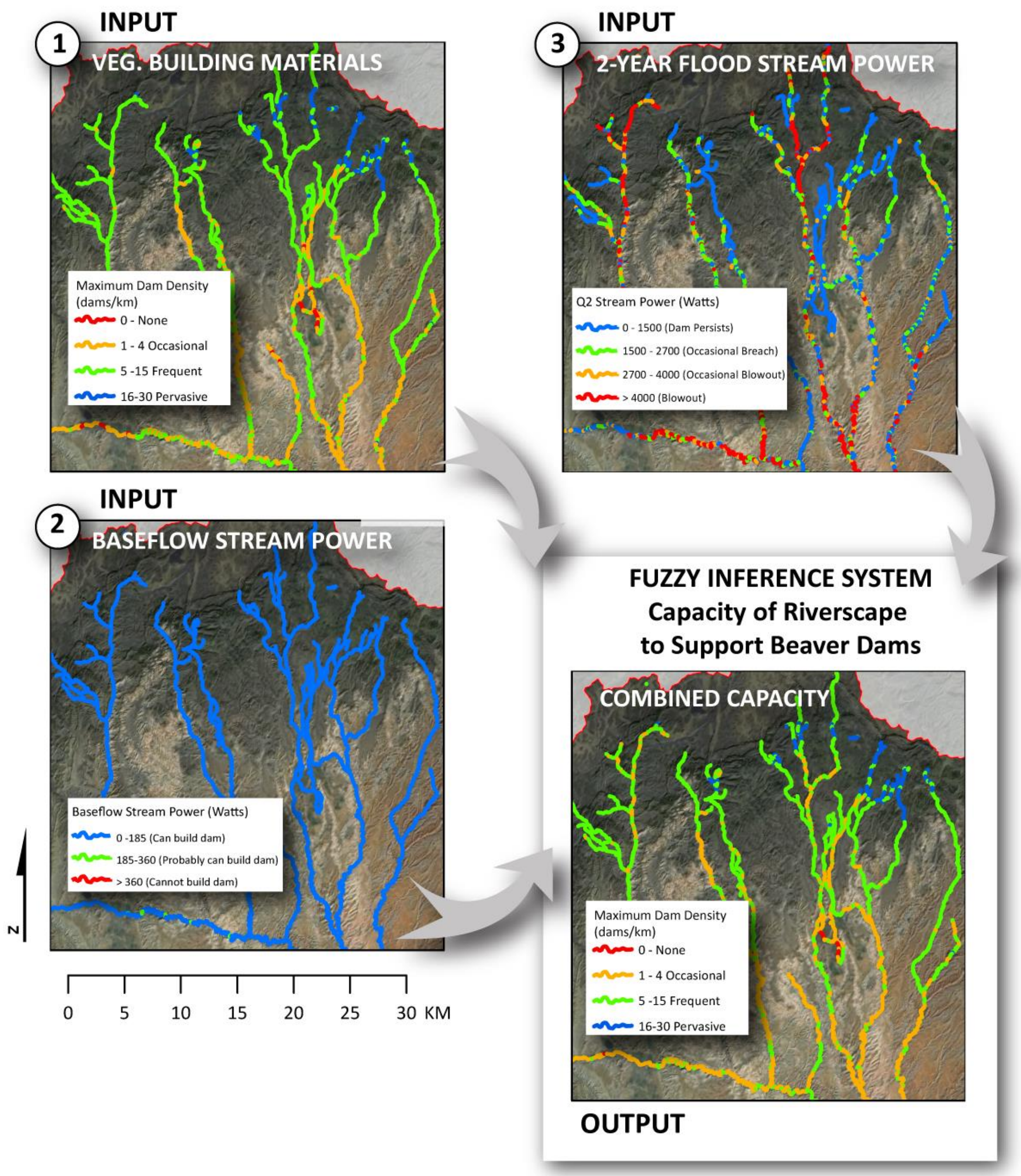


Figure 13 – Methodological illustration of inputs and output for combined model of capacity of riverscape to support beaver dam building activity (output expressed in dam density).

MODEL VERIFICATION

A capacity model is difficult to 'validate' truly because rarely, if ever, would the entire riverscape be at 'capacity'. However, since the model output is in dam density, it can be directly compared to actual dam densities. Where the system is 'at capacity', a direct comparison can serve as a validation, whereas elsewhere relative concentrations of dams and an assessment of whether or not the riverscape can accommodate further dams can be made. Given the scope of this pilot project, our ability to verify the model was limited. However, we did leverage what data we had on active and historic dam locations in the Escalante watershed, Logan River and Blacksmith Fork watersheds of Utah. Current numbers of beaver are rather limited in the Escalante watershed due to over a century of active trapping, discouraging beaver and land use practices not intended to promote beaver. In the Escalante we visited and ground truthed locations where the Grand Canyon Trust (p. comm. Mary O'Brien) had monitored and located active dams. Additionally, we investigated areas where conditions seemed adequate to support beaver dam activity and located historic remnants and evidence of beaver dams and evidence of paleo distributary channel networks associated with former dam activity. We also conducted an aerial assessment of the current and historic distributions of beaver dams in the catchment with a rapid overflight (Macfarlane et al., 2013) with the help of EcoFlight (http://ecoflight.org). The accuracy and usability of the environmental parameter data (NHD and LANDFIRE land cover) were field verified using overflights and ground-based surveys in key areas. The objectives of the ground verification were to determine the accuracy of NHD perennial stream coding (i.e., if a stream was coded as perennial was flowing water detected) and to determine the accuracy of the LANDFIRE vegetation mapping of the riparian areas. The NHD estimation of perennial versus intermittent streams (Figure 8) was validated for the entire drainage network during overflights and proved remarkably accurate. Despite relatively coarse pixel resolution (30 m for LANDFIRE) on the vegetation, ground-truthing and overflights revealed that LANDFIRE was consistently able to correctly identify the presence of key woody species even in streams with very narrow riparian ribbons.

Model validation and calibration were also conducted in the Logan River and Blacksmith Fork watersheds in northern Utah, an area where reliable data correlating stream power and beaver dam establishment and persistence exists (Lokteff et al., 2013). The Logan and Blacksmith watersheds are ideal as validation sites because the main stems of each of these rivers have just large enough stream powers that dams are occasionally built but do not persist throughout a given year- (i.e., spring runoff breaches and blows out these dams), whereas the lower order tributaries are home to very high densities of beaver. In addition, spring 2011 high flows allowed for the calibration of stream power (i.e., what stream power was necessary to breach and blow out dams. Extensive beaver dam census data also exists for these watersheds.

OTHER LIMITING FACTORS FOR BRAT

The beaver dam capacity model outlined above works essentially by combining the essential ingredients beaver need for building dams (perennial water source and vegetative building materials) with the most significant hydraulic forces that might limit dam building activity (stream power at low flows versus high flows). As already mentioned, a variety of other factors can limit the capacity of the riverscape to support beaver dam building, such as exposure to predators (including humans), proximity to roads, or proximity to human infrastructure. One such limiting factor in a western US context can be lack of woody vegetation due to overgrazing by ungulates. To illustrate how ungulates and other potential limiting factors can be incorporated into BRAT eventually, we constructed a simple ungulate capacity model, to highlight where on the landscape beaver dam building might be limited by preferred grazing areas.

UNGULATE OCCUPANCY MODEL

Heavy ungulate browsing in riparian areas can reduce the distribution and abundance of woody riparian species, especially cottonwood and willow, because they are highly preferred browse. This in turn can severely limit the ability of these systems to support dam-building beaver (Case and Kauffman, 1997; Hood and Bayley, 2008b). As a proof of concept, we developed a simple, probabilistic ungulate occupancy model. Like the beaver model, it is driven by LANDFIRE vegetation data, which we classify by its suitability as forage for cattle in this case (Figure 22). Numerous other researchers have highlighted the importance of the composition of plant communities for ungulates (Senft et al., 1985). Similarly, distance to a reliable water source (Holechek, 1988) and slope (Ganskopp and Vavra, 1987) have been highlighted as key factors influencing where ungulates are likely to congregate. We derived slope (as a percent) from a 30 m USGS DEM and we derived distance from water (in meters) using a simple Euclidian distance geoprocessing algorithm with perennial streams, springs and water bodies as inputs. We used concurrent 30 m rasters of classified vegetation, distance to water and slope to estimate the probability of ungulate occupancy in a given 30 m pixel based on the rules outlined in Table 3. Membership functions were calibrated for slope and Euclidian distance based on values reported in the literature.

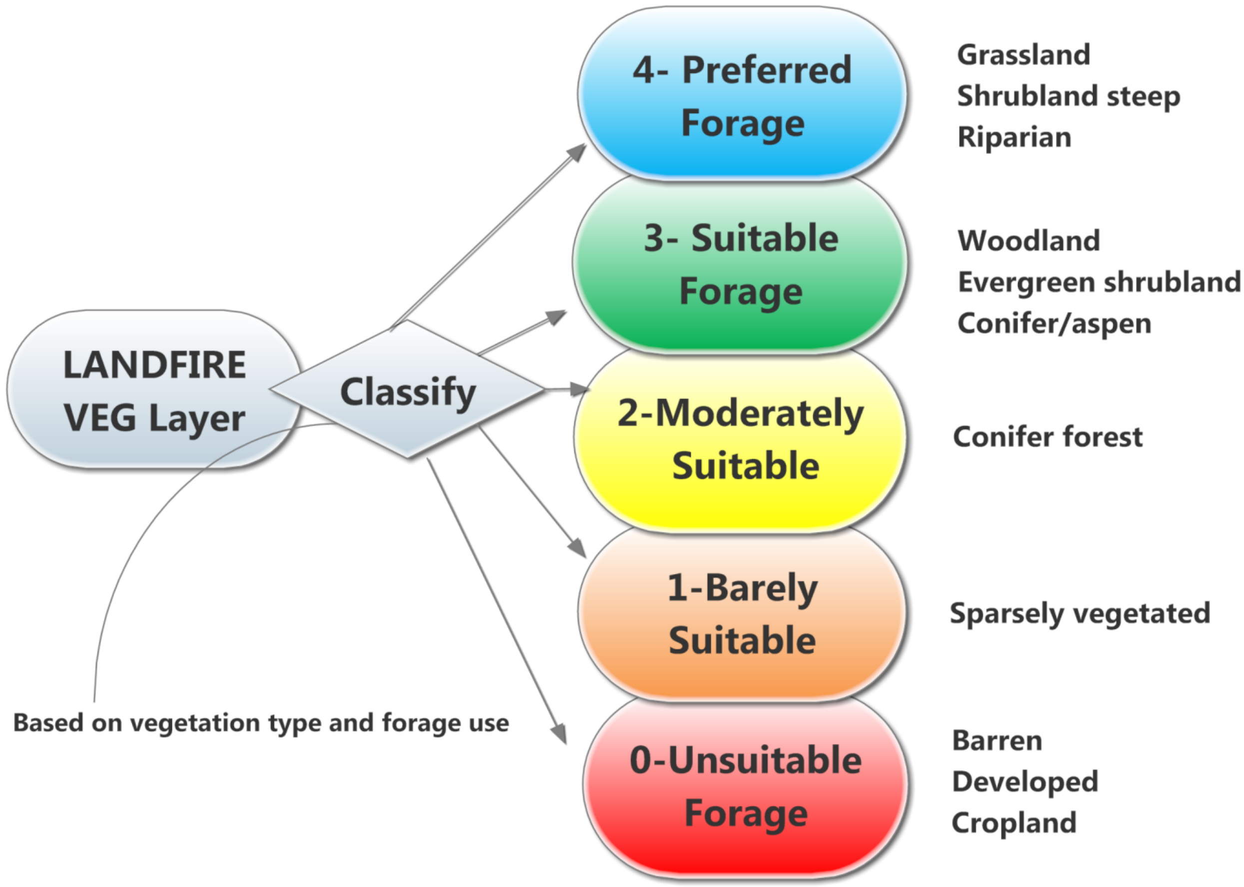


Figure 14 - Classification of suitability of vegetation (from LANDFIRE) as ungulate forage.

Table 3 - Rule table for three-input fuzzy inference system that models the probability of ungulate occupancy on the landscape using the vegetative suitability for grazing, slope and distance to a perennial water source as inputs.

	INPUTS						OUTPUT
IF	Vegetation Suitability for Grazing		Slope (%)		Distance to Perrenial Water Source		Proability of Ungulate Occupancy
RULES 1	Unsuitable	&	-	&	-	, then	None
2	Barely Suitable	&	Flat	&	Close	, then	Low
3	Moderately Suitable	&	Flat	&	Close	, then	Low
4	Suitable	&	Flat	&	Close	, then	Moderate
5	Preferred	&	Flat	&	Close	, then	High
6	Barely Suitable	&	Gentle	&	Close	, then	Low
7	Moderately Suitable	&	Gentle	&	Close	, then	Low
8	Suitable	&	Gentle	&	Close	, then	Low
9	Preferred	&	Gentle	&	Close	, then	Moderate
10	Barely Suitable	&	Too Steep	&	Close	, then	Low
11	Moderately Suitable	&	Too Steep	&	Close	, then	Low
12	Suitable	&	Too Steep	&	Close	, then	Low
13	Preferred	&	Too Steep	&	Close	, then	Low
14	Barely Suitable	&	Flat	&	Moderately Far	, then	Low
15	Moderately Suitable	&	Flat	&	Moderately Far	, then	Low
16	Suitable	&	Flat	&	Moderately Far	, then	Low
17	Preferred	&	Flat	&	Moderately Far	, then	Moderate
18	Barely Suitable	&	Gentle	&	Moderately Far	, then	None
19	Moderately Suitable	&	Gentle	&	Moderately Far	, then	Low
20	Suitable	&	Gentle	&	Moderately Far	, then	Low
21	Preferred	&	Gentle	&	Moderately Far	, then	Low
22	Barely Suitable	&	Too Steep	&	Moderately Far	, then	None
23	Moderately Suitable	&	Too Steep	&	Moderately Far	, then	None
24	Suitable	&	Too Steep	&	Moderately Far	, then	Low
25	Preferred	&	Too Steep	&	Moderately Far	, then	Low
26	Barely Suitable	&	Flat	&	Too Far	, then	None
27	Moderately Suitable	&	Flat	&	Too Far	, then	None
28	Suitable	&	Flat	&	Too Far	, then	Low
29	Preferred	&	Flat	&	Too Far	, then	Moderate
30	Barely Suitable	&	Gentle	&	Too Far	, then	None
31	Moderately Suitable	&	Gentle	&	Too Far	, then	None
32	Suitable	&	Gentle	&	Too Far	, then	None
33	Preferred	&	Gentle	&	Too Far	, then	Low
34	Barely Suitable	&	Too Steep	&	Too Far	, then	None
35	Moderately Suitable	&	Too Steep	&	Too Far	, then	None
36	Suitable	&	Too Steep	&	Too Far	, then	None
37	Preferred	&	Too Steep	&	Too Far	, then	Low

RESULTS

CAPACITY OF LANDSCAPE TO SUPPORT BEAVER DAMMING

We show the results of the derivation of model inputs first and then how they culminate in the output to the beaver dam capacity model.

MODEL INPUTS

EVIDENCE OF WOOD FOR DAM BUILDING MATERIALS

Figure 15 shows the distribution of the suitability of existing vegetation as a dam building material throughout the Escalante. The preferred materials show the highest concentrations in the upper portions of the tributaries as they flow through and originate in the base of the escarpment and upper slopes of Boulder Mountain. As shown in Figure 10, these areas have extensive aspen forests. There are also areas of preferred materials where partly-confined valley bottoms in otherwise deep bedrock gorges are able to support thriving riparian corridors. These areas exist both in the dissected benchlands and on the mainstem Escalante gorge but tend to be limited to small pockets. Most of the tributaries draining Boulder Mountain show fairly extensive areas of suitable building materials along the streams that descend to the Escalante mainstem. The Escalante gorge shows pockets of this suitable material more extensive than the pockets of preferred materials. The lower gorge transitions into unsuitable and barely suitable materials simply because of the aridity of the lower gorge and the backwater from Lake Powell.

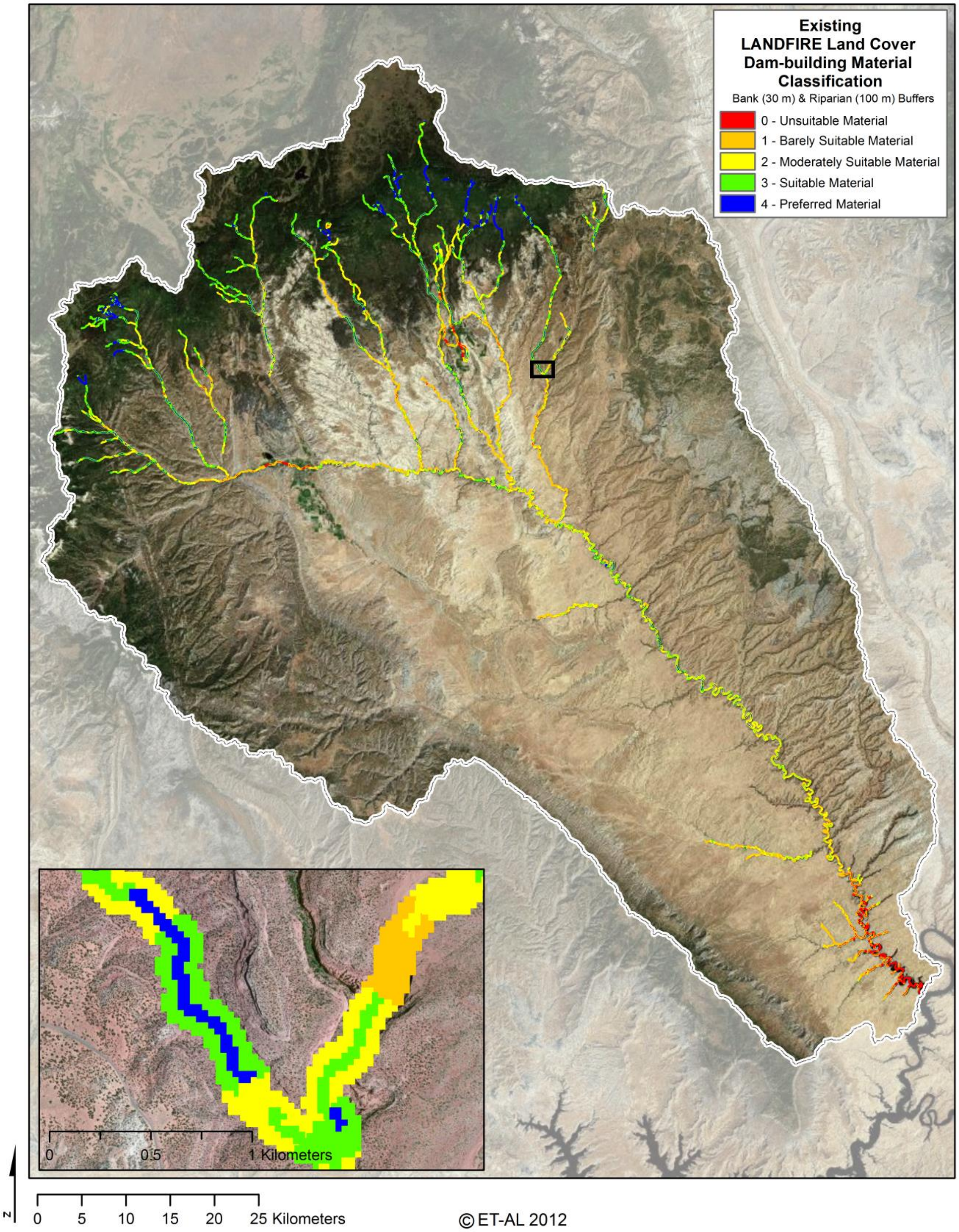


Figure 15 – Results of classification of LANDFIRE vegetation into suitability as dam building material along stream banks (30 m buffer) and within broader riparian zones (100 m buffer).

EVIDENCE THAT A BEAVER DAM CAN BE BUILT VERSUS PERSIST

Figure 16 shows the results of stream power derived for typical September baseflows (i.e., discharge exceeded 80% of the time in September). Vast majority of the map is classified as 'can build dam' with stream powers well below 185 watts. Given that summer baseflows even on the mainstem hover around a trickle at 0.28 m^3s^{-1} (Christensen and Bauer, 2005), this is not at all a surprising result. Flows on 99% of the perennial streams in the Escalante are not high enough to prevent a beaver from building a dam and are therefore not limiting. However, there are short reaches scattered about the Escalante gorge and some of the feeder gorges that are steep enough and confined enough that their stream powers might interfere with a beaver's ability to build a dam.

The two year recurrence interval peak flow stream powers shown in Figure 17 show much more interesting patterns. Most of the first and second order tributaries show stream powers less than 1500 watts and dams would likely persist in these flows. Included in this is virtually all of Calf Creek. Some of the steeper portions of the lower parts of the east and west forks of Boulder Creek, as well as significant portions of Pine Creek have a mix of predicted blowouts and potential blowouts. By contrast, most of Birch Creek, North Creek, Sand Creek, Deer Creek and Steep Creek alternate between locally steep areas with predicted occasional breaches and areas where dams are likely to persist. The mainstem has a high concentration of alternating extremes between areas predicted to blow out and areas predicted to persist. This is not surprising given its overall higher stream powers (often > 4000 watts). So in summary there is little evidence to suggest that beaver dams cannot build dams at baseflow if adequate building materials exist, but where those dams are likely to persist is highly dependent on locality.

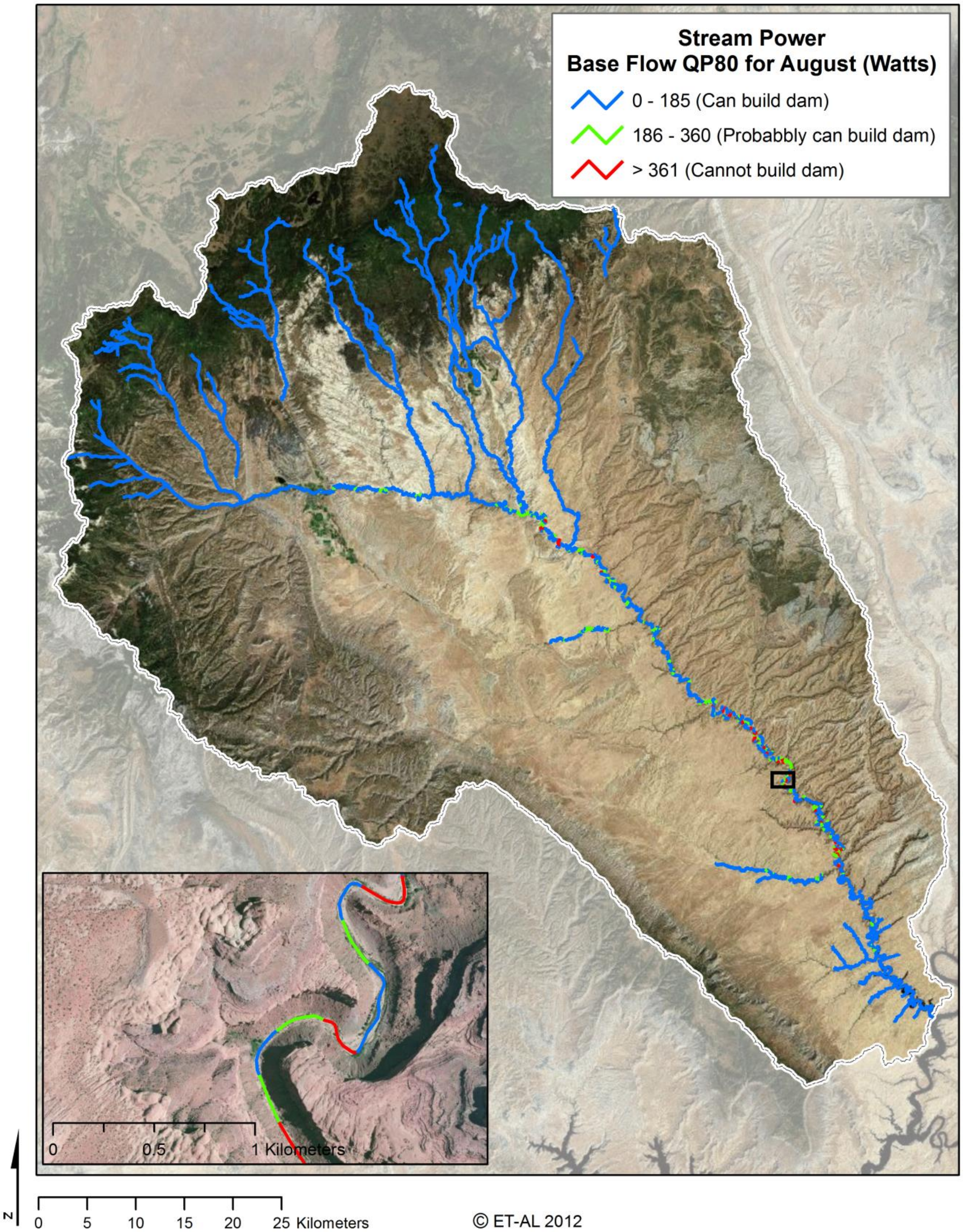


Figure 16 – Evidence that beaver can build dams at base flows based on stream power estimates.

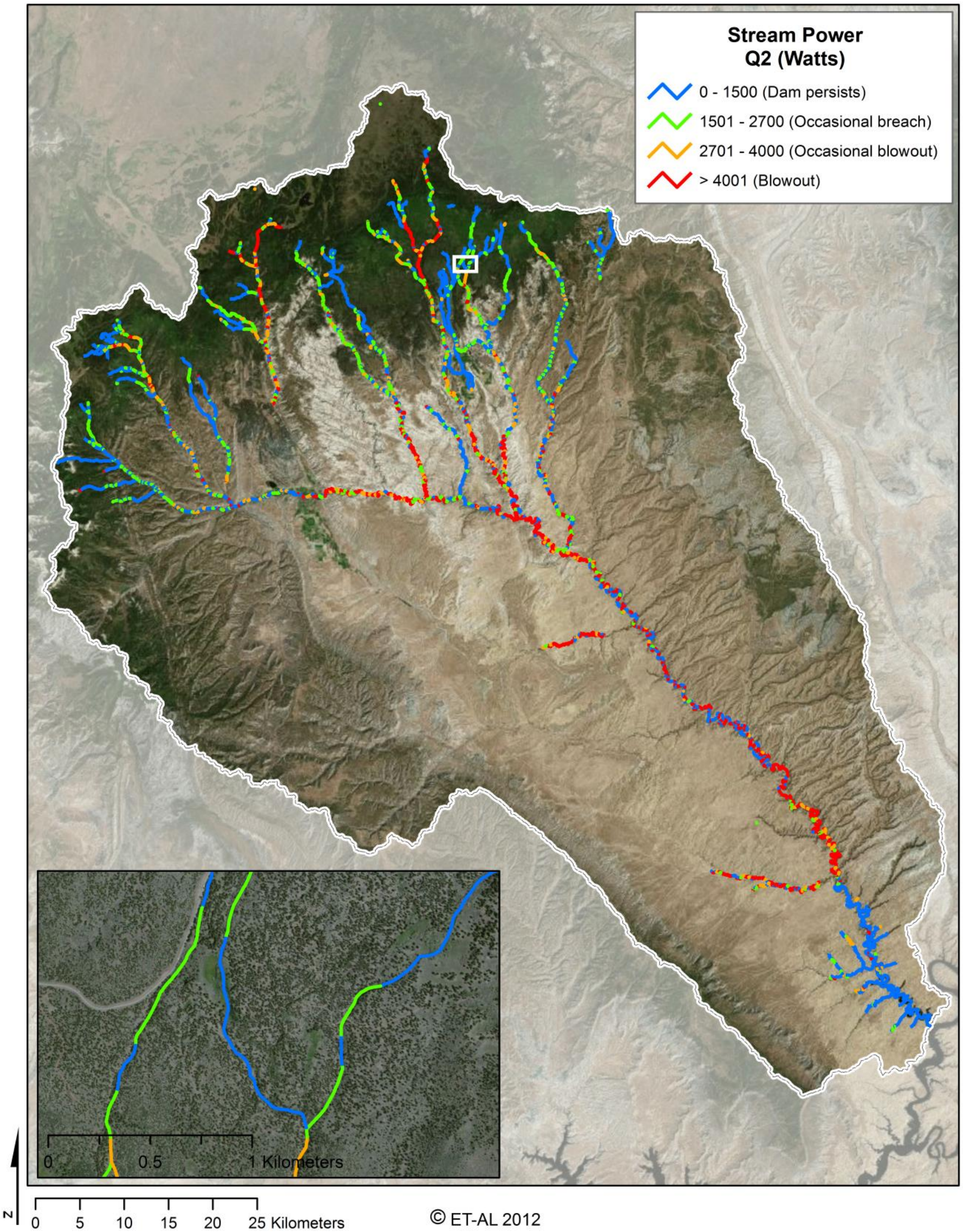


Figure 17 – Evidence about whether or not beaver dams are likely to persist during high flows based on stream power.

MODEL OUTPUT

When combined using the beaver dam capacity fuzzy inference system, the inputs produce the patterns shown in Figure 19. The results are primarily driven by the vegetation suitability patterns set up in Figure 15, with some lowering of predicted dam density capacities in areas with high stream powers from Figure 17. The only areas with pervasive maximum dam densities predicted are those first and second order tributaries up at the base of the escarpment, which intersect the band of aspen. Moving downstream there is a high occurrence of predicted 'frequent' dam densities and the further downstream one goes towards and into the mainstem Escalante, dam densities become generally 'occasional'.

Since the patterns in Figure 19 are so similar to those of the vegetation model (Figure 17), it is helpful to look more closely at the impact of incorporating stream power in the model. Figure 18 demonstrates the impact of those areas with peak stream powers that can potentially blow out dams (Figure 17) on the distribution of stream segments with 'none', 'occasional', 'frequent' and 'pervasive' predicted maximum densities. There is essentially a shift from 'frequent' to 'occasional'.

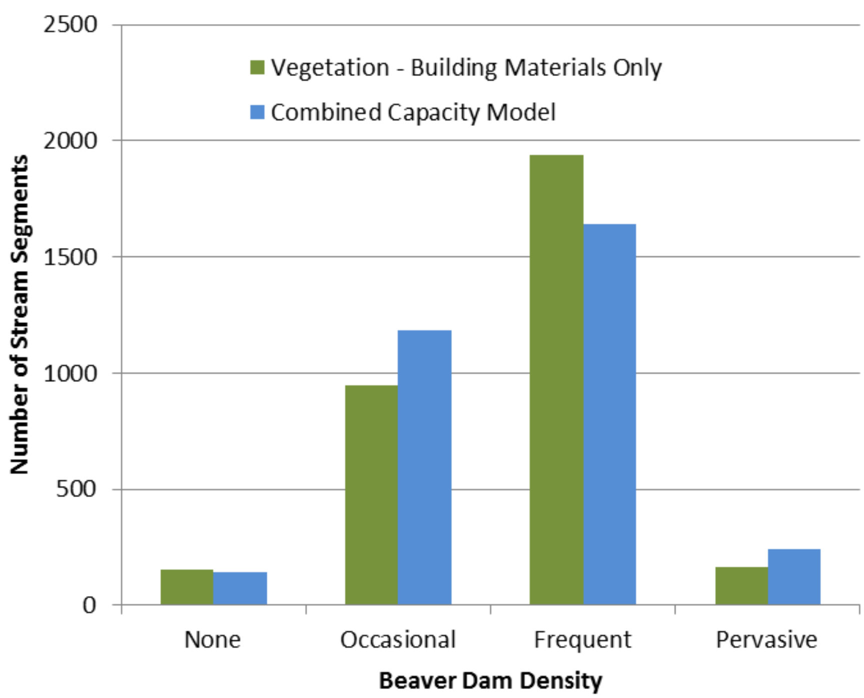


Figure 18 – Comparison of beaver dam densities between the final model output and the dam density model driven only by dam building materials.

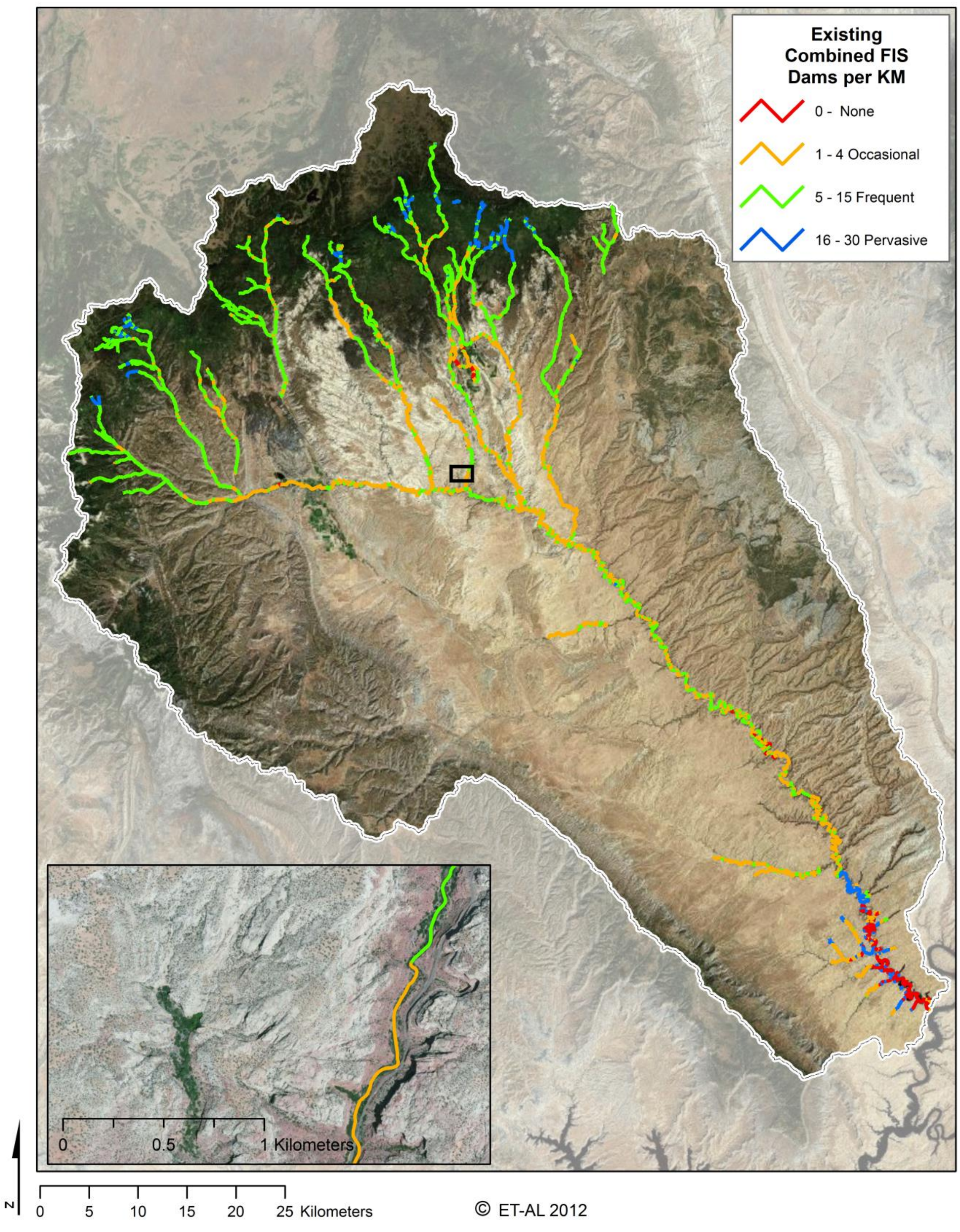


Figure 19 – Results of beaver dam capacity model based on existing conditions. The perennial portion of the drainage network is symbolized in categories of dam density (dams per kilometer).

SCENARIO COMPARISON – POTENTIAL VEGETATION

As an illustration of how different scenarios can be explored, we drove the model with all the same inputs, except that the LANDFIRE vegetation was a potential vegetation model (based loosely on crudely approximated historic vegetation) instead of an existing vegetation model (from 2008). Other possible scenarios one could explore include manipulating vegetation values in the input to reflect restoration and/or climate change scenarios, and/or manipulating the hydrology (through changes to baseflow and/or peak flows) to explore different climate change scenarios. Figure 20 shows the comparison of the two LANDFIRE vegetation inputs, existing based on 2008 LANDSAT (Figure 20a), and historic potential (Figure 20b). Most of the differences in vegetation suitability are along the mainstem Escalante both in the reaches near the town of Escalante and in the lower Escalante Gorge. In Figure 20c & d, we can see the subtle manifestation of these slight differences in vegetation in the transformation of areas predicted for being able to support 'occasional' beaver dams to much more area being able to support 'frequent' beaver dams. Figure 21 illustrates this difference by contrasting the percentage of stream segments showing the different categories of beaver dam densities. If one multiplies the model output for each segment (number of dams/kilometer) by the length of the stream segment and sums them all, you can have a rough approximation of the total number of beaver dams the system could support at FULL capacity (note this number would likely never be realized even under pre-European settlement conditions as factors like predation and competition might limit these numbers). The existing full capacity estimate for the entire Escalante watershed is 6531 dams, whereas the potential full capacity estimate in this scenario is 7679 dams. Over the roughly 814 km of perennial streams in the catchment, those upper estimates correspond to only subtly different overall dam densities of 8.0 dams/km and 9.4 dams/km respectively. These numbers fall in the 'frequent' category, and importantly not in the 'pervasive' category. With the notable exception of the high elevation areas around the escarpment, the vast majority of the Escalante is a harsh desert environment where wood is limiting.

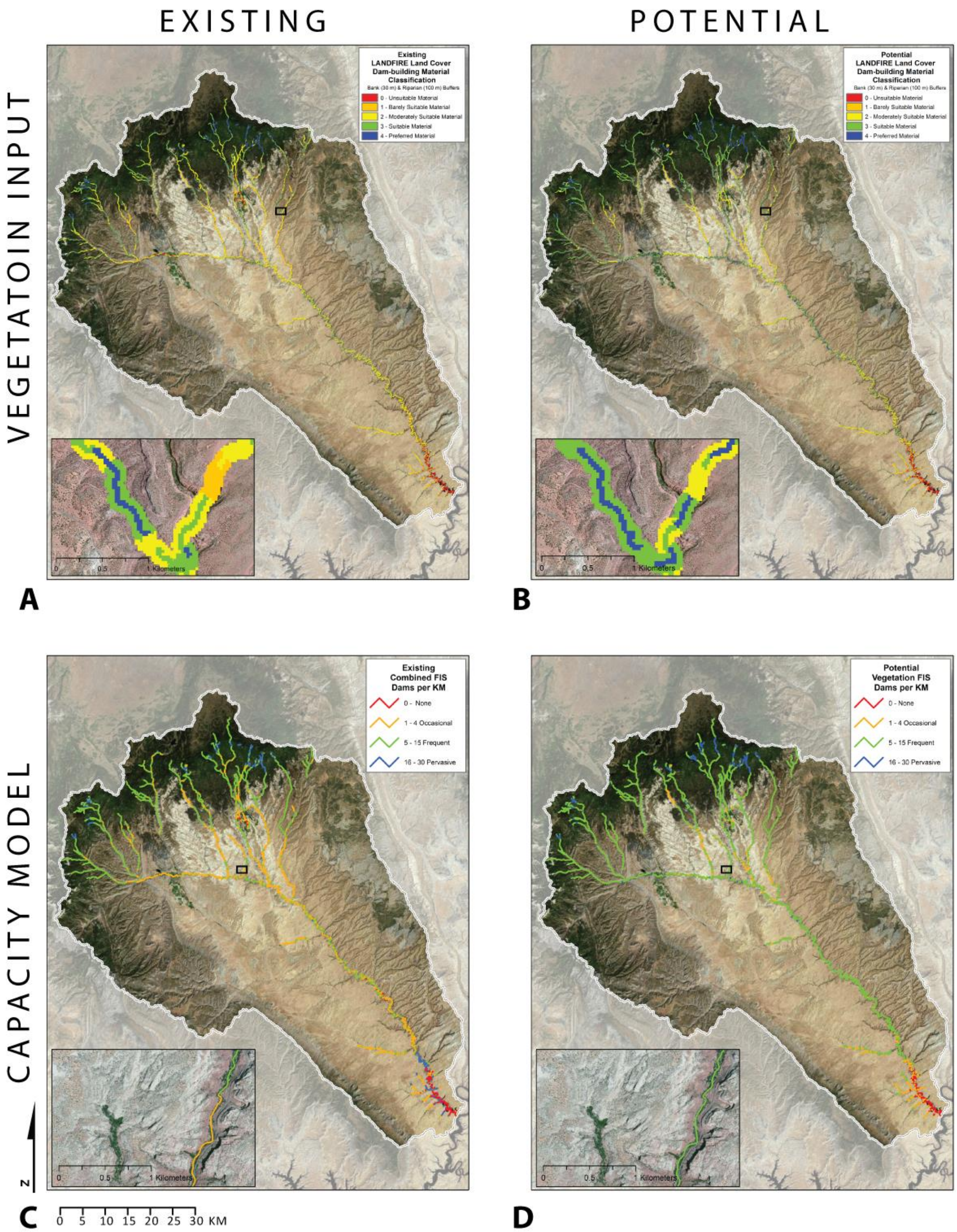


Figure 20 - Comparison of existing (left – A & C) versus potential (right - B & D) LANDFIRE vegetation for dam building material (top – A & B) versus predicted maximum beaver dam densities (bottom – C & D).

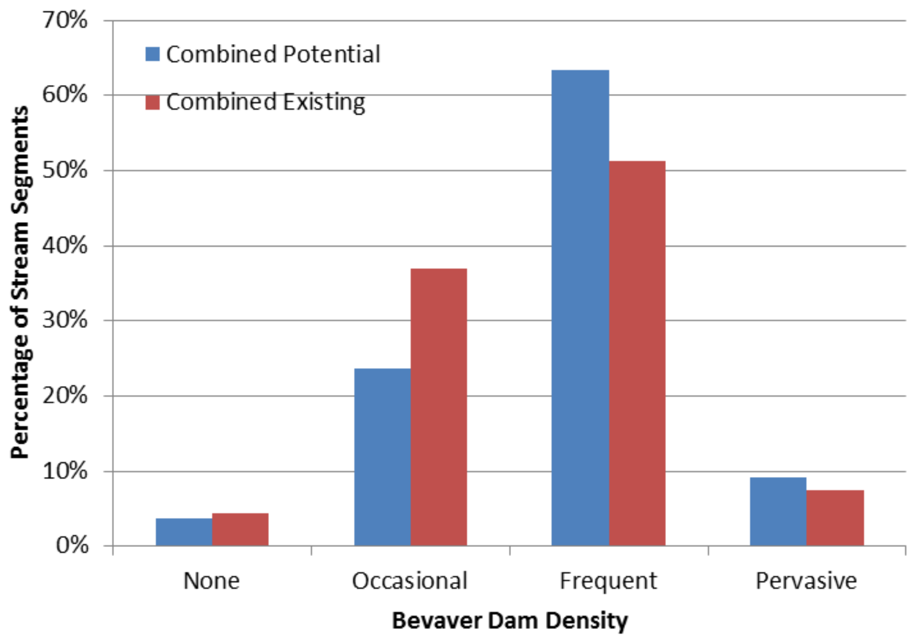


Figure 21 – Comparison of potential versus existing maximum beaver dam densities by percentage of stream segments.

UNGULATE OCCUPANCY MODEL

The ungulate occupancy model was driven by three inputs: vegetation suitability (Figure 22), distance from water sources (Figure 23) and slope (Figure 24). The vegetation is the strongest driver and not surprisingly we see the strongest concentration of suitable and preferred forage along the base of the escarpment up on Boulder Mountain (US Forest Service lands) and along the tablelands to the southeast of the Escalante gorge and extending up to and around the town of Escalante (Figure 22). Most of the area up around Boulder Mountain with suitable and preferred forage is fairly close to water sources, but many areas of the tablelands are too far from perennial water sources (Figure 23). When these inputs are combined with slope (Figure 24) and subjected to the rules in Table 3, some coherent patterns of probability of ungulate occupancy emerge in Figure 25. Namely, areas along the outside the town of Escalante, around Boulder and further up on Boulder Mountain show up. Some of the areas showing up as high probability are actually areas used for arable agriculture, but many of the areas are within active allotments and do indeed see high concentrations of ungulates. Information on allotment concentrations is limited, but could be collected to better validate the patterns shown here.

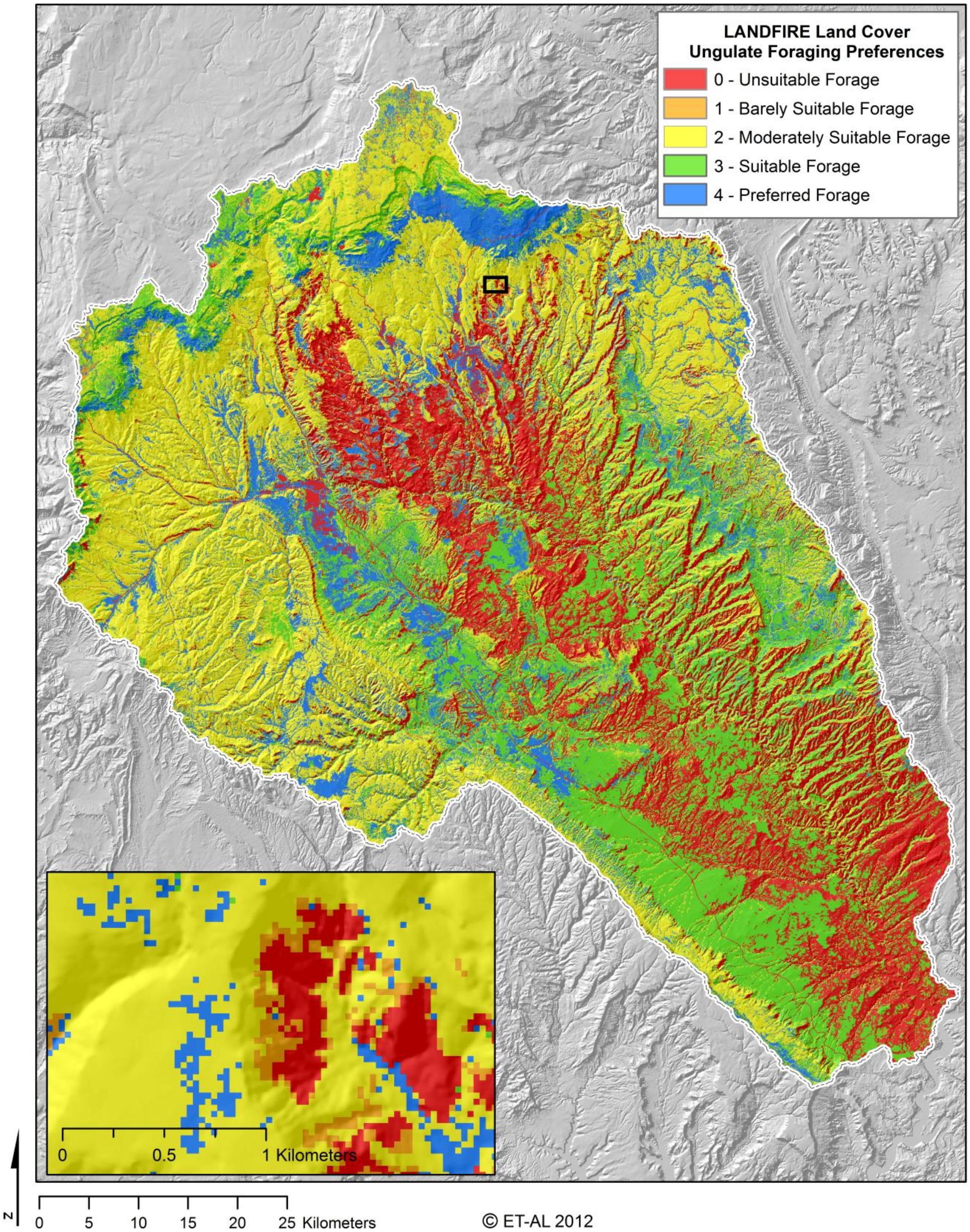


Figure 22 – Classification of LANDFIRE vegetation in terms of forage suitability for ungulates. This is an input into the ungulate occupancy model.

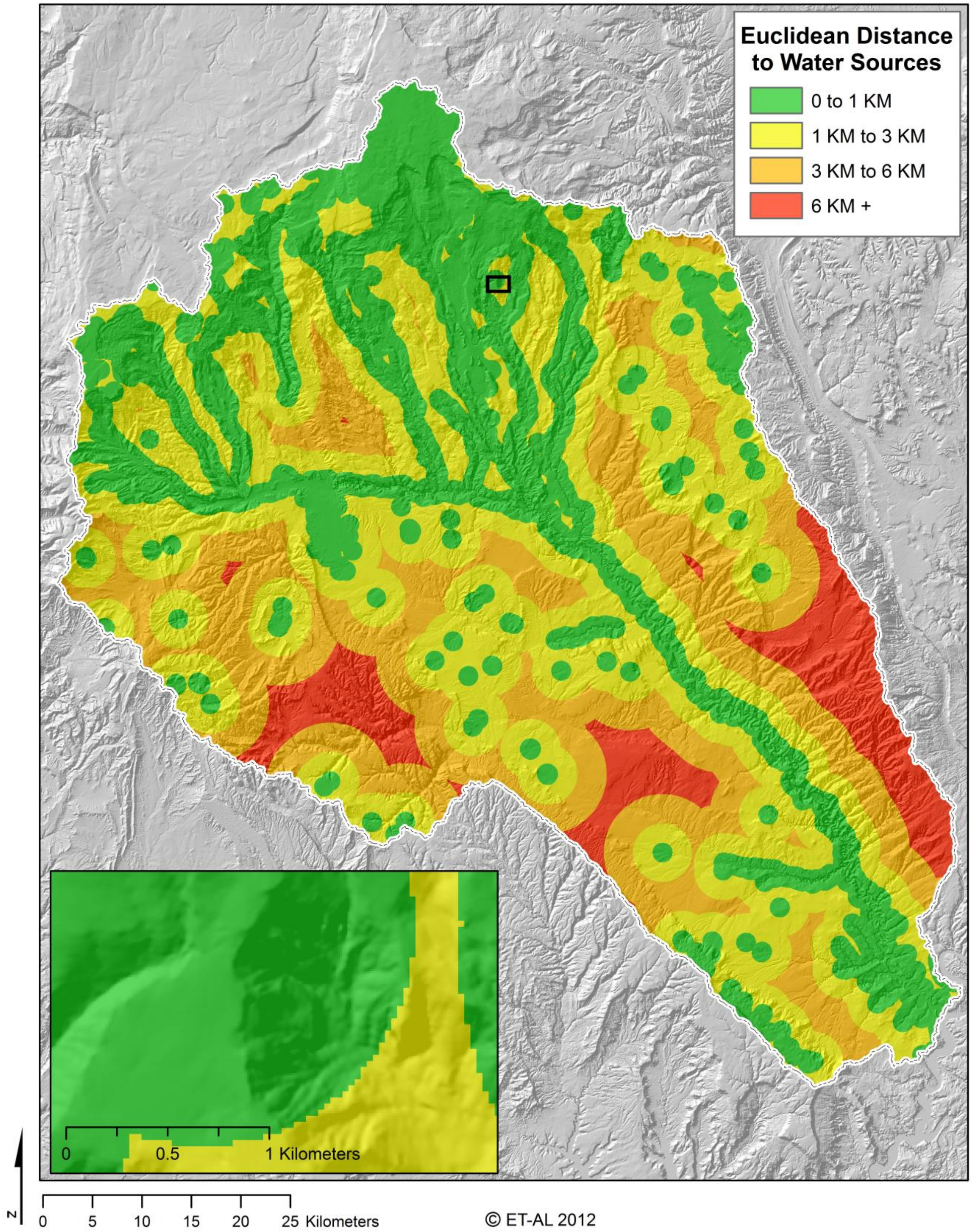


Figure 23 – Distance to perennial water sources (streams, springs and ponds). This is an input to the ungulate occupancy model.

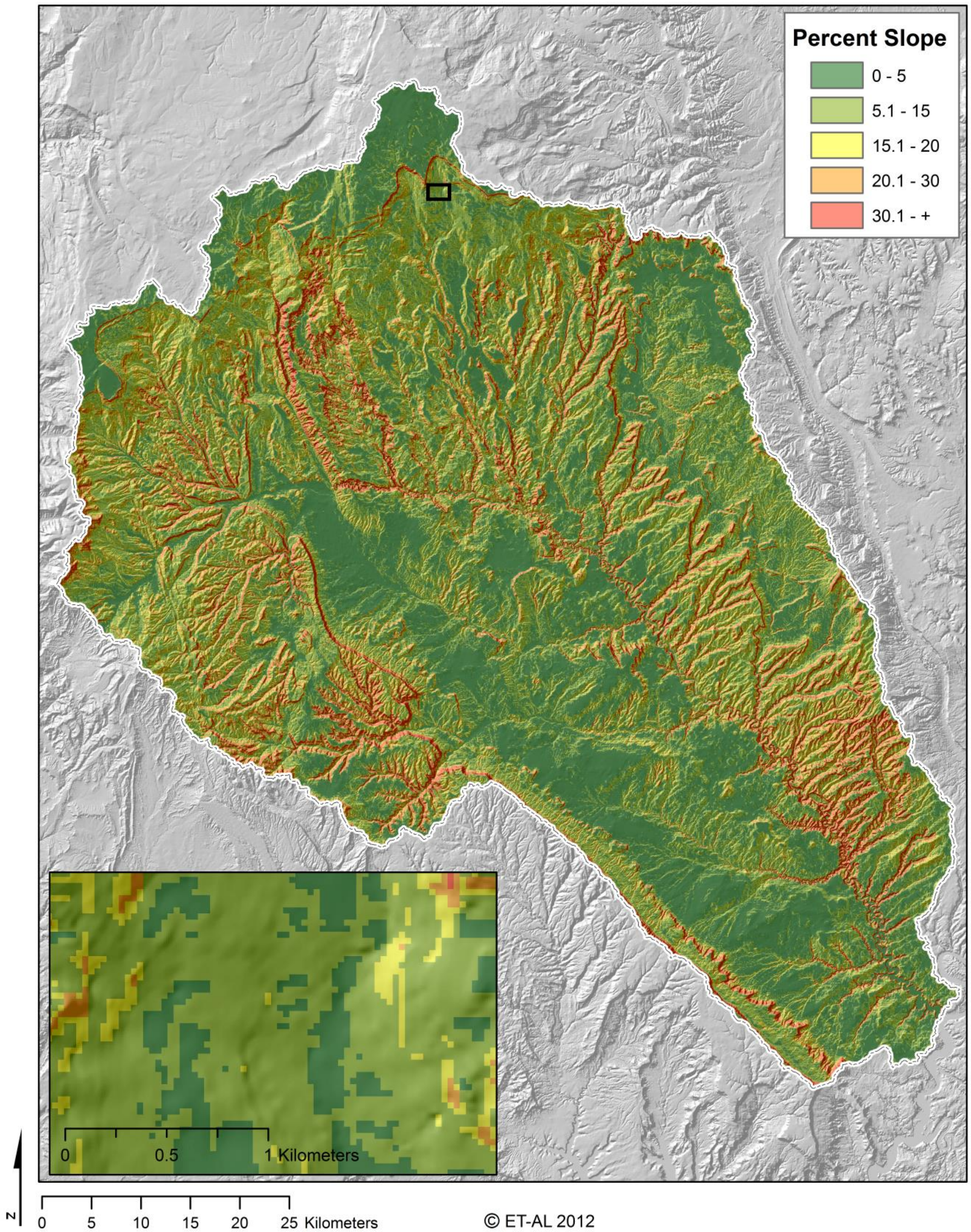


Figure 24 – Slope analysis (in percent slope) of 30 m DEM, which acts as an input to the ungulate occupancy model.

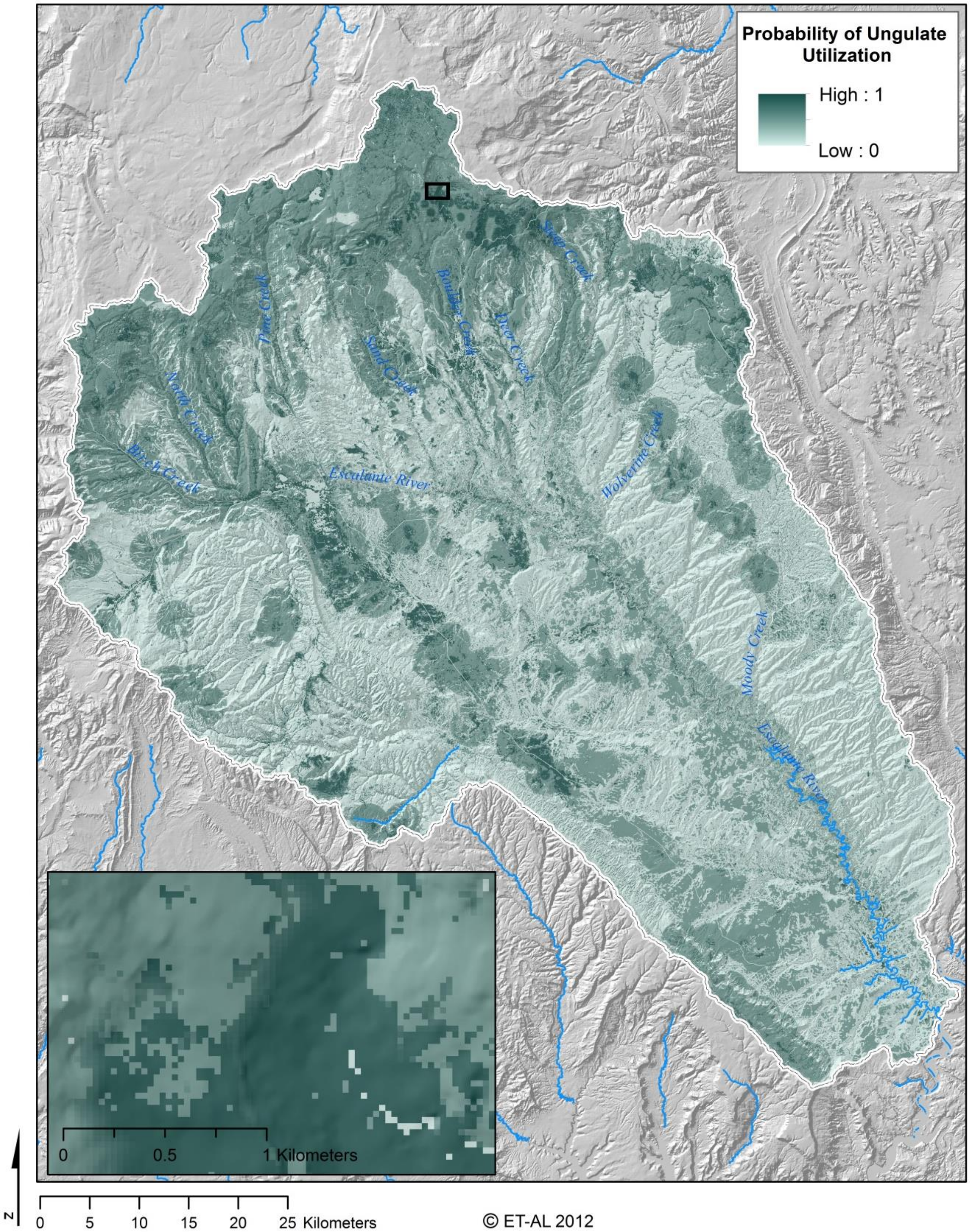


Figure 25 – Probabilistic ungulate occupancy model, based on fuzzy inference system using vegetation suitability, slope and distance to perennial water source as inputs.

EXAMPLE OF MODEL VERIFICATION

The performance of habitat suitability models is typically 'validated' or 'bioverified' based on a comparison of model predictions to utilization data (Pasternack, 2011). If higher densities of utilization correspond to areas of higher quality predicted habitat, and lower densities or no utilization correspond to areas of low quality predicted habitat, the models are considered to perform well. Since we did not have comprehensive data in the Escalante to perform such verification, we ran the beaver dam capacity model for the Logan River and Blacksmith Fork watersheds of northern Utah. An example of how well the model compared (with no calibration) to actual dam survey data from Lokteff et al. (2013) in the Temple Fork watershed is shown in Figure 26. The model does a remarkable job of distinguishing between areas with high densities of dams (dam complexes with number of dams are shown as circles in Figure 26) and those areas with no dams or smaller concentrations of dams.

For example, a large persistent dam complex on Spawn Creek has shown up in aerial photos going back to at least the 1950s. This complex had 11 dams within two segments totaling about 350 meters (i.e., dam density of 31 dams/km) and the model pinpoints the lower segment as having pervasive dams (15 – 30 dams/ km) and upper segment as having frequent dams (5-15 dams/km). Dam densities go up and down in this reach as the colonies working here go through periods of intensive harvesting and activity and then rest parts of the complex and move upstream or downstream for periods of 5-10 years. This is an area where dam densities fluctuate but is likely near capacity.

Downstream of this complex on Spawn Creek, two new dams showed up in 2010 near an ATV bridge (denoted as stars in Figure 26). These are likely dams from a dispersing beaver and they show up in a reach where the riparian vegetation has been slowly recovering following a passive restoration that removed cattle from the reach in 2005 (Hough-Snee et al., In Review). The model predicts occasional beaver dams in this reach (1-5 dams/kilometer) and this is what we find. We speculate that over time this reach will see higher dam densities as the riparian vegetation continues to recover post intensive grazing pressure and can support more dam building.

On Temple Fork, where grazing is more prevalent, there are currently roughly 10 beaver dams in the three kilometers upstream from the Spawn Creek confluence (3.3 dams/km). This entire reach is predicted as being able to support occasional beaver dams (1-4 dams/km). Given the relative lack of riparian and upland vegetation to support further expansion, we speculate this reach is persisting at a relatively low capacity. For higher densities to exist, we would need to see the recovery of a greater expanse of riparian vegetation in this area.

During exceptionally high spring runoff flows in 2011, the largest dam in the uppermost dam complex (4 dams) in this reach on Temple Fork was breached and another dam completely blew out. Those beaver apparently dispersed and in the fall of 2011 12 dams showed up in a 250 m reach (20.8 dams/km) roughly a half kilometer upstream. What is really remarkable is that with absolutely no calibration the model pinpointed within 30 meters the boundaries of this reach and differentiated from neighboring reaches as being able to support pervasive dam densities (15-30 dams/km). Compared to the upstream and downstream reaches, this reach boasts a readily available supply of aspen within the 30 m and importantly the 100 m buffers, as well as a slightly lower slope and lower peak flood stream powers. It is worth noting that this reach did not have any dams in it for at least the past decade.

The fact that a model driven with such coarse resolution (10 m DEMs and 30 m LANDFIRE) readily available is able to consistently make capacity predictions that compare favorably to actual dam densities is very encouraging. We need to extend these verification tests to much larger datasets and diverse physiographic regions. However, the model does appear to effectively segregate the primary factors controlling beaver dam occurrence.

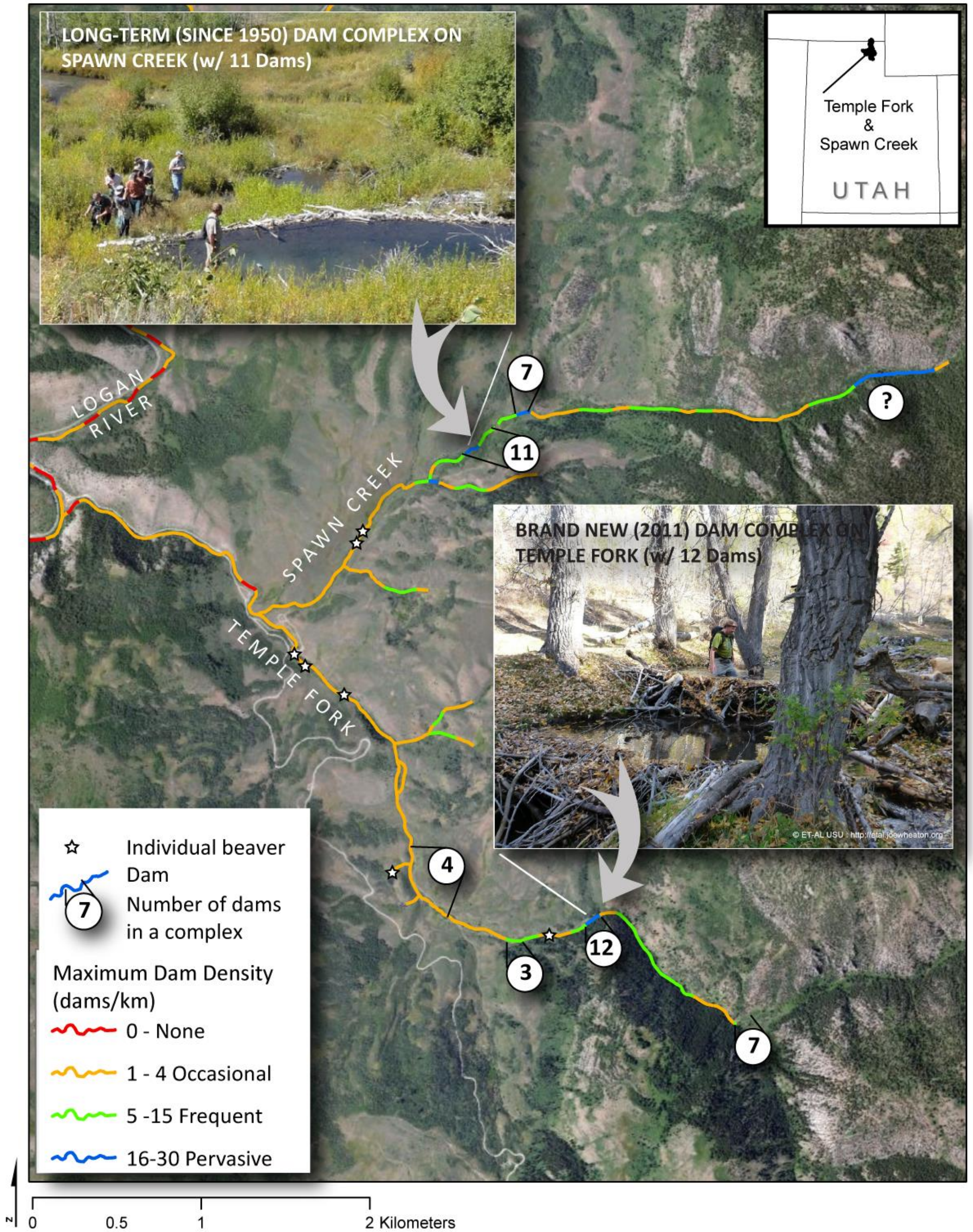


Figure 26 – Example of verification of beaver dam capacity model peformance in the Temple Fork wateshed (tributary to Logan River). Individual beaver dams are denoted with white stars, whereas dam complexes are shown in circles (number in circle is count of dams) in discrete segments.

DISCUSSION

TRADITIONAL HABITAT SUITABILITY MODELS VS. BEAVER DAM CAPACITY MODEL APPROACH

BRAT is a spatially explicit beaver dam capacity assessment tool, and to our knowledge, it is the first of its kind. Rather than attempting to assess beaver habitat suitability, which is not only very difficult for a highly adaptable generalist like beaver, but more importantly has proven to be unreliable, BRAT relies on assessing the capacity of a given landscape to support dam-building beaver (i.e., dams per km). We focus on dam building activity, because from a restoration perspective that is precisely the ecosystem engineering that provides the most ecosystem services. The resulting capacity information helps determine where reintroduction or conservation of beaver populations is appropriate and where it is not. By focusing on dam-building beaver capacity, the source of beaver's ecosystem services, streams and rivers with high stream power are eliminated from consideration in the capacity model approach. A traditional beaver suitability model might identify such streams as highly suitable even though nothing other than dispersing beaver might build temporary dams in them.

MANAGEMENT/RESTORATION IMPLICATIONS

As more stream and riparian restoration plans are developed in the western US that utilize beaver, there is a pressing need to be able to assess where on the landscape we may get the 'biggest bang for our buck'. With restoration facing criticism for its expensive price tags, questionable results and limited spatial extents, beaver are well poised to help provide a 'cheap and cheerful' alternative to standard projects (Wheaton et al., 2012). Beaver and the dams they build can increase aquatic habitat complexity and allow the stream channel to reconnect with its floodplain allowing for regeneration of native riparian species. Using beaver is appealing not only because of the cost savings compared to traditional approaches that use heavy equipment to re-create stream channels, but also because beaver are an important historic component of these ecosystems. However, the success of the restoration plans will depend very much on the capacity of riverscapes to support dam-building beaver. Beaver will not simply thrive everywhere we want them to and there are many places that might not support dam building activity at all.

The capacity model presented provides an excellent tool in the toolbox to begin to explore where in the landscape might be appropriate locations to employ beaver. The capacity model alone will not be enough to build realistic restoration plans with beaver. These models need to be combined with other lines of evidence that present practical limitations to dam-building beaver (e.g., proximity to potential human conflicts like road/culvert crossings, irrigation diversions, and ungulate overgrazing). An example is shown in Figure 27 where we overlay probability of ungulate grazing with the beaver dam capacity model. Such information can be combined to highlight potential conflicts between high beaver capacity and high ungulate occupancy. In our pilot project proposal we envisioned that with BRAT we would eventually be able to differentiate streams into five categories 1. Low hanging fruit streams, 2. Quick return streams, 3. Long-term possibility streams, 4. Naturally limiting streams, and 5. anthropogenically limiting streams. We elaborate on their definitions and occurrence in the Escalante below:

1. **Low-hanging Fruit Streams** – Many riparian habitats are either currently inhabited by beaver or are in relatively good condition for beaver recolonization. The focus of management in these streams should be conservation of these biodiversity hotpots and the hydrologic, geomorphic and ecosystem processes that maintain them, as well as pursuing expansion or reintroduction of beaver (e.g., trapping and relocation of 'nuisance' beaver colonies from areas where they are in direct conflict with human activity). Although the current extent of beaver dams in the Escalante watershed is rather limited (likely <200), there are at least two streams that could be considered low-hanging fruit streams: portions of North Creek, and Calf Creek upstream of the campground. In both cases, beaver are already thriving and grazing pressure is currently limited (though historically was a major limitation up until the 1980s).
2. **Quick Return Streams** – Many streams currently lack riparian conditions necessary to support beaver (e.g., incised or heavily grazed streams), but can, with minimal intervention and changes in management practices (e.g., cattle grazing exclosures), exhibit relatively rapid fluvial responses that allow for beaver recovery and subsequent maintenance of such conditions. For example, in Eastern Oregon using cheap and biodegradable fence posts as beaver dam support structures, we have been able to increase dam life and beaver damming activity, resulting in dramatic streambed aggradation, which promotes reconnection with former floodplain surfaces and increases complexity of in-channel and floodplain habitats (e.g., Pollock et al. 2012). In the Escalante, there are a number of obvious candidate quick return streams at the base of the escarpment where numerous springs emerge and a broad band of aspen exist (Figure 10). Streams like the east and west branches of Boulder Creek, Sand Creek, Pine Creek, Upper North Creek and Birch Creek are all potential quick return streams. However, these streams would require changing grazing management with active efforts to develop off-channel water sources for ungulates, and encouraging them to spend less time in the riparian areas (either with riders pushing them, or fencing of the riparian areas).

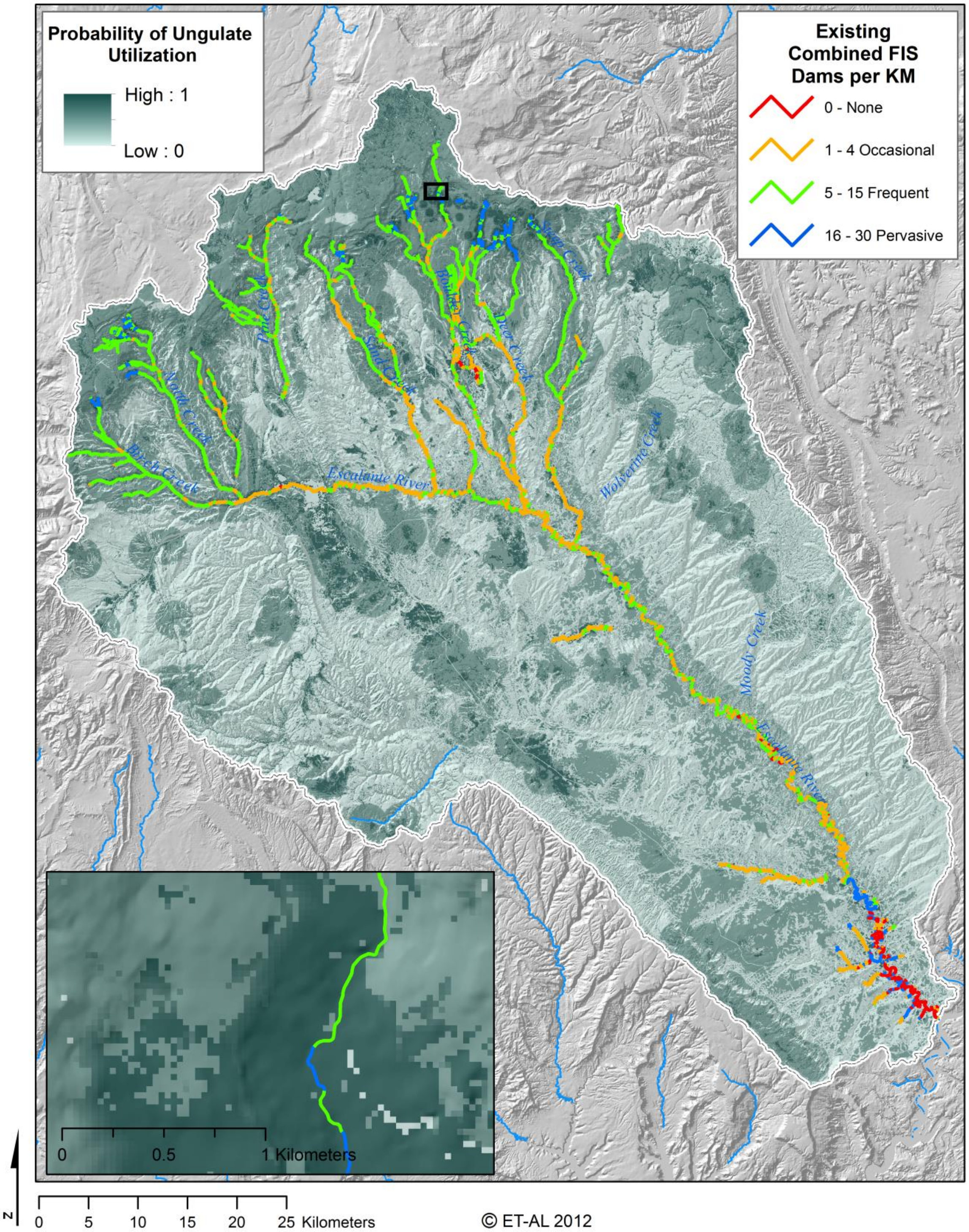


Figure 27 – Combined outputs of the beaver dam capacity model and probabilistic ungulate occupancy model. BRAT will eventually provide a framework for managers to consider potential conflicts and opportunities. The inset map shows a classic potential conflict where there is the possibility to support frequent or pervasive beaver dams, but also a very high probability of ungulate utilization. This is an area where if beaver are to be used successfully as a conservation/restoration agent, grazing management would need to limit ungulate access to the riparian areas.

3. **Long-Term Possibility Streams** – Other streams may show potential in terms of colonization by beaver, either because they historically supported beaver populations or could provide the right habitat conditions. However, these systems are not immediately obvious candidates for promoting active dam building beaver populations due to land-use commitments or expense of recovering habitat conditions. Land managers may strategically decide to pursue conservation efforts in these streams because of their position in the drainage network and/or their value. Many of the streams dissecting the semi-arid bench lands (Figure 4) of the Escalante might fall into this category. Even some of the most over-grazed reaches of streams further up Boulder Mountain near the escarpment would require recovery of riparian vegetation before they can support decent beaver populations.
4. **Unsuitable, Naturally Limited Streams** – Prior to European settlement and trapping of beaver in North America, there would always have been some streams and rivers that were unsuitable for colonization by dam-building beaver. These included streams that were too small, ephemeral, or steep; lacked adequate wood resources for foraging and building; and/or were too large to dam (although floodplain and side-channel habitat may be potentially colonized). In Figure 27, there are relatively few of the perennial streams in the Escalante that would fall under this category, but all the intermittent streams in Figure 8 fall into this category.
5. **Unsuitable, Anthropogenically Limited Streams** – Some streams will be unsuitable for beaver because humans constrain their habitat conditions (e.g., water quantity, water quality, and/or wood availability), or there are human-beaver conflicts (e.g., beaver blocking irrigation canals). With the incredibly low population density in the Escalante, not many streams in Figure 27 fall under this category. However some of the streams adjacent to agricultural developments around the towns of Boulder and Escalante could be considered unsuitable because of potential conflicts with other water/land uses.

We do not provide a map of these five stream types because these categories rightly involve a mix of quantitative evidence (like the capacity models we present here) and more subjective and value-laden input from interested stakeholders, land users (e.g., allotment holders, farmers, hunters, recreationists), and land managers. This is precisely what we hope BRAT can do eventually: provide a framework for transparently combining the science and practical realities and priorities on the ground to classify the drainage network.

FUTURE WORK

The most pressing future work needed to follow on from this pilot project is to develop the BRAT. With the completion of this pilot project, the capacity model is done. The next steps are to i) combine this model with the above components to complete the construction of BRAT; ii) verify and refine performance of BRAT across a diverse range of physiographic settings; and iii) test the utility of BRAT in different restoration and management contexts.

We see BRAT becoming a powerful research and restoration/conservation planning tool for questions relating to where in the landscape dam-building activity by beaver might be sustainable and at what sort of dam densities. At the heart of this is a capacity model that models the capacity of the landscape to support dam-building activity by beaver. What will translate this from a simple capacity model to an assessment tool will be the ability to:

- Combine with other layers that limit realization of capacity (e.g., grazing pressure)
- Combine with management layers (e.g., proximity to potential “nuisance” sites, forestry, grazing, irrigation, roads, and agriculture) to look at areas of potential management conflicts.
- Combine with River Styles to look at restoration potential (e.g., reconnection of floodplains in incised streams)
- Develop and explore different scenarios that represent management options (e.g., riparian fencing or installation of beaver dam support structures) as well as different climate change scenarios (e.g., changing flow regimes).
- Use as a basis for economic valuation of ecosystem services provided by beaver dams (e.g., Buckley et al., 2011)

VERIFICATION MONITORING

To help with the further verification aspect, we are partnering with the Utah State University Water Quality Extension team to develop a state-wide beaver monitoring program (p. comm Brian Greene). The Grand Canyon Trust’s volunteer program will be one of the first groups to pilot the new protocol. We are actively working to develop tablet and smartphone apps to collect this spatially explicit information and automatically upload it to a central database when cellular or internet connections are re-established for the devices. An example of the type of spatially-explicit data volunteers will be trained to collect is shown in Figure 29. The spatial location of dams alone will help build a geodatabase of dam occurrence from which dam densities can be derived and compared directly with model capacity predictions. The additional of auxiliary data will help test specific aspects and assumptions of the model. We could also use the data to calculate an electivity index (e.g., Pasternack, 2011) for different habitats, with ‘frequent’ and ‘pervasive’ presumed to show high electivity and ‘occasional’ and ‘none’ to show low electivity.

Figure 28 – Participants in the ‘Partnering with Beaver in Restoration Design’ workshop (http://beaver.joewheaton.org) conducting rapid assessment beaver dam surveys.

BEAVER DAM & ACTIVITY MONITORING FORM

OBSERVATION INFO

Observer Name: ______________________

Site ID: ______________________

Observation Date: ______________________

STATUS
- o Active
- o Abandon
- o Historic/Relic

OBSERVATION TYPE:
- o Beaver Dam
- o BDSS
- o Beaver Activity (no dam)

CONFIDENCE IN STATUS
- o Certain - Documented Evidence
- o Probable - Strong Evidence
- o Possible - Anecdotal or Inconclusive Evidence
- o Unsure - Just a guess

OBSERVATION CHRONOLOGY
- o New Observation of New Feature
- o First Observation of Existing Feature
- o First Observation of Relic Feature
- o Repeat Observation of Existing Feature

FLOW CONDITION
- o Baseflow
- o Spring runoff
- o Flood
- o Post Flood

POSITIONAL ATTRIBUTES

GPS UTM Easting: ______________________

GPS UTM Northing: ______________________

PART OF DAM COMPLEX?

Dam Complex ID ______________________

- o Start of new dam complex
- o Existing dam complex
- o NA - Isolated Dam
- o NA - Non-Dam

DAM LOCATION RELATIVE TO CHANNEL(S)
- o On Main Channel
- o On Right Side Channel(s)
- o On Left Side Channel(s)
- o On Left Floodplain
- o On Right Floodplain

DAM ATTRIBUTES AT TIME OF SURVEY (IF APPLICABLE)

Max dam height (m) +/- 0.1 m __________

Max pond depth (m) +/- 0.1 m __________

Water Surface Difference (m) (m) +/- 0.1 m __________

Dam Length (m) (m) +/- 1 m __________

DISTANCE UPSTREAM OF POND BACKWATER
- o < 5 m
- o 5 - 10 m
- o 10 - 25 m
- o 25 - 50 m
- o 50 - 100 m
- o > 100 m

FLOODPLAIN INUNDATION
- □ During Extreme Floods - River Right
- □ During Extreme Floods - River Left
- □ During Seasonal Floods - River Right
- □ During Seasonal Floods - River Left
- □ Year Round Inundation - River Right
- □ Year Round Inundation - River Left

SIDE CHANNELS
- □ None
- □ Single Left
- □ Multiple Left
- □ Single Right
- □ Multiple Right

DAM MATERIALS USED (CIRCLE DOMINANT)
- □ Woody branches > 15 cm diameter
- □ Woody branches < 15 cm diameter
- □ Mud
- □ Grass / Reeds
- □ Other organic
- □ Cobble or Boulders

POND EXTENT
- o Contained within bankfull channel
- o Expanding out onto floodplain
- o Drained

ESTIMATED DAM AGE
- o < 1 year
- o 1-3 years
- o 3-5 years
- o 5 -10 years
- o > 10 years

DAM CONDITION (IF APPLICABLE)

FLOW TYPES

(Specify Value 0-100%; Sum should be 100%)

Flow Over Top	____
Basal Flow	____
Throughflow	____
Flow Around Left	____
Flow Around Right	____
Total Check =	100%?

DAM BREACH OR BLOWOUT

o In-tact
o Minor breach (< 25 cm height) on left
o Minor breach (< 25 cm height) on right
o Minor breach (< 25 cm height) on center
o Minor basal breach
o Major breach (> 25 cm height) on left
o Major breach (> 25 cm height) on right
o Major breach (> 25 cm height) on center
o Major basal breach
o Blowout (whole height of dam breached)

POND CAPACITY

o Clean o Minor Sedimentation
o Partial Filling (upto 50% of original pond capacity)
o Major Filling (50% to 95% of original pond capacity)
o Full of sediment (no longer a pond)

DOMINANT SUBSTRATE IN DEEPEST PART OF POND

o Fines (clays and silts) o Sands
o Gravels o Cobble
o Food Cache & Fines

DOMINANT SUBSTRATE AT POND ENTRANCE

o Fines (clays and silts) o Sands
o Gravels o Cobble
o Food Cache & Fines

NOTES:

RECENT BEAVER ACTIVITY:

Only answer all questions with respect to recent (past 6 months)

DAM EXPANSION

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

DAM CONSTRUCTION

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

DAM MAINTENANCE

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

SCENT MOUND

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

CANAL DIGGING

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

POND EXCAVATION

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

DAM NOTCHING

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

DRAINING/FLUSHING

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

CORN ON THE COB (FORAGING)

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

FELLING OF TREES

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

HARVESTING OF BRANCHES

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

SKID TRAIL USAGE

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity
o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

PRIMARY WOOD HARVESTED

o Aspen o Cottonwood
o Willow o Other Hardwoods
o Conifers o No active harvesting

ABOVE GROUND LODGE MAINTENANCE OR CONSTRUCTION

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

BANK LODGE MAINTENANCE OR CONSTRUCTION

o Certain - Documented Evidence o Probable - Strong Evidence
o Possible - Anecdotal or Inconclusive Evidence
o Unsure - Just a guess o No Evidence of Activity

Figure 29 – Pages 1 and 2 of Draft Beaver Dam Monitoring Form to be used by volunteer beaver monitoring crews.

HIGHER RESOLUTION CAPACITY MODELS

Data in this pilot was deliberately obtained from relatively coarse, nationally available data sources. This was to ensure that the capacity models and BRAT could easily be extended as a first order or better planning tool over large regions (e.g., Western US). However, the capacity models can easily accommodate higher resolution, more refined inputs. For instance, higher resolution riparian vegetation data (e.g., classified vegetation layers from ≥1 m resolution mulit-spectral imagery) could be substituted for the 30 m resolution LANDFIRE data to have a more accurate building materials input. For example, reach-averaged slopes are currently derived from 10 m or 30 m resolution NED DEMs, but more refined slopes could be calculated from LiDaR data. Including additional environmental factors is also easily doable and could improve and refine the model. For example, Barnes and Mallik (1996) found that dam construction was based on size (diameter) of plants rather than species preferences. Therefore, if data on the diameter of riparian plants were available these data could be input data in the beaver dam capacity model. Similarly, if stream-width data were available, it could be used to calculate unit stream power which would provide a more useful estimate than total stream power does.

FUTURE BRAT TOOLS

We envision BRAT consisting of a series of transparently documented methods that any experienced GIS Analyst could deploy and implement manually. Indeed, the capacity models presented here are transparently documented and could be reproduced (see Deliverables section). However, we think we could make BRAT more useful to managers, practitioners and researchers if we could deploy it as:

- A WebGIS application that would allow users to:
    - Explore and visualize a Base-Version of BRAT run for the Western US in a Google Maps interface
    - Run and produce simple BRAT scenarios
    - Export BRAT outputs as KML or shapefiles
- An ArcGIS Plugin or Add-In that would allow users to:
    - Download and modify Base-Version of BRAT for area of interest
    - Run and produce BRAT scenarios based on customized user inputs

These ideas and this vision are laid out on the publically accessible BRAT website: http://brat.joewheaton.org.

CONCLUSIONS

This pilot project illustrates the power of combining GIS analysis, fuzzy inference system and capacity modeling. The emerging Beaver Restoration and Assessment Tool (BRAT) could be a cost effective, rapid-assessment landscape-scale management tool for identifying the capacity of the landscape to support dam-building beaver activity at the reach-level (250 m stream segments). The capacity models in BRAT also proved to be easily transferable and flexible to apply in other basins (e.g., the Logan River & Blacksmith Fork watersheds) due to the use of nationwide data and, where available, detailed local data. Transferability was a key aspect of the capacity model's design because the overarching goal was to determine if an accurate method could be developed for use by land management agencies to prioritize streams for beaver-assisted restoration not only in the Escalante River watershed but in the three national forests of southern Utah, across Region 4 and eventually nationwide. We conclude that the spatially explicit capacity data produced here could be combined in BRAT to help resource managers in the Escalante River watershed identify potential beaver conservation and relocation sites for further evaluation. To improve and extend the usability of BRAT we advocate further testing, refinement and calibration. We also believe that making BRAT into a web application and an ArcGIS add-in will allow the tool to be easily and effectively used by resources managers. We hope to apply the approach to the three national forests in southern Utah as well as broader geographic regions (e.g., Western US) to explore both the restoration/conservation implications of beaver as well as broader scientific questions about the impacts of potentially achieving higher beaver dam densities on the timing, storage and delivery of water, sediment and nutrients in riverscapes.

ACKNOWLEDGEMENTS

This research was made possible primarily because of the vision, persistence and support of Mary O'Brien at the Grand Canyon Trust. Mary secured funding through the generosity of the Walton Family Foundation and then Grand Canyon Trust awarded a sub-award to the Ecogeomorphology & Topographic Analysis Lab at Utah State University. This project would not be possible without the collaboration of Grand Canyon Trust and Utah State University, Watershed Sciences Department, Ecogeomorphology and Topographic Analysis Lab. Funding for this research was provided by the Walton Family Foundation Freshwater Initiative that focuses on sustaining healthy and resilient communities of both wildlife and people in two of our country's most important river systems the Colorado and Mississippi River Basins.

We thank Bruce Gordon and Jane Pargiter at EcoFlight, for their support and for donating flight time and resources to conduct a rapid assessment overflight of the Escalante watershed. Professor Dennis Bramble generously hosted us during field work in Escalante and shared with us some his insights into the geomorphic evolution of the Escalante. We thank Jeremy Christenson from Grand Canyon Trust and Sage Sorenson (retired BLM) for their help in the field. Sage's knowledge of the history of Calf Creek was particularly helpful. Finally, the development of the model benefitted greatly from insights and conversations with Nick Bouwes (Eco Logical Research), Chris Jordan (NOAA), Nate Hough-Snee (USU), Ryan Lokteff (USU), Michael Pollock (NOAA), Brett Roper (USFS), and John Stella (SUNY).

DELIVERABLES

There were two specified deliverables for this pilot project:

1. A report summarizing the effectiveness of this approach for mapping suitable riparian vegetation and beaver occurrence and restoration priorities in other areas of the National Forest System.
2. A beaver habitat suitability GIS database that identifies current and potential beaver habitation and highlights priority streams for beaver reintroduction in the Escalante River watershed of the Dixie National Forest.

This report satisfies the first deliverable. We have posted all the GIS data for the second deliverable at: http://etal.usu.edu/GCT (Figure 30):

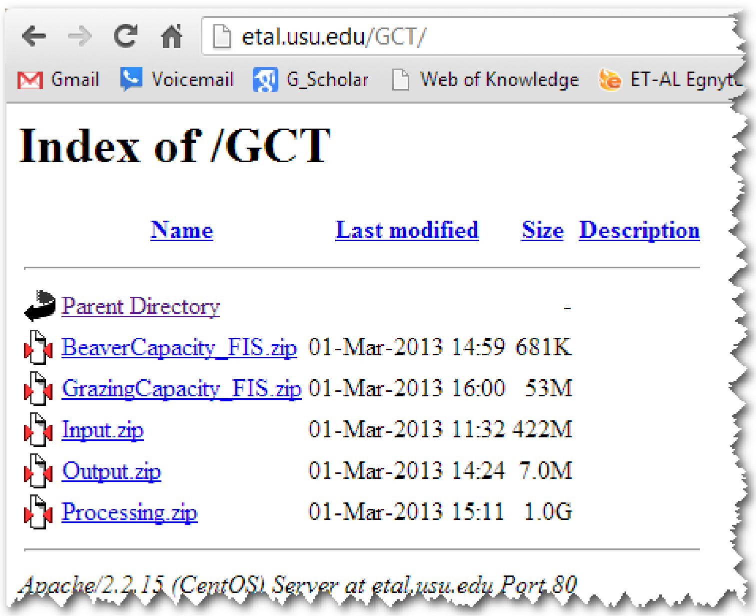
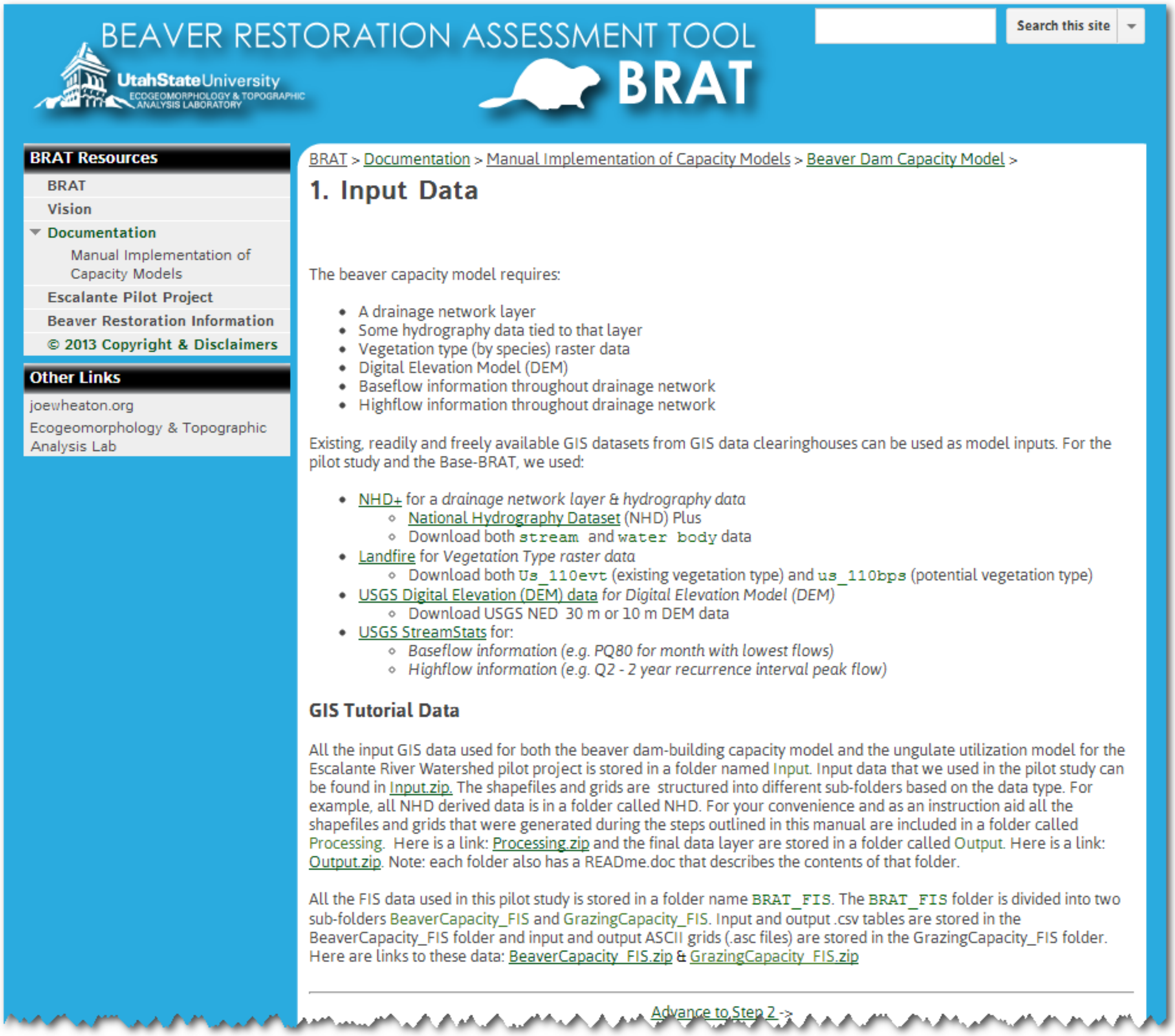


Figure 30 – The deliverable directory on the ET-AL website for the GIS Data (Input.zip, Output.zip, Processing.zip) and the FIS models (BeaverCapacity_FIS.zip & GrazingCapacity_FIS.zip).

In addition we have prepared an online instruction manual at http://brat.joewheaton.org for how to manually do the analysis using the Escalante as an example (Figure 31). Note that the Matlab code for the beaver capacity model will require modification and updating of the regional curve equations for it to be applied in other regions.



BEAVER RESTORATION ASSESSMENT TOOL
UtahStateUniversity ECOGEOMORPHOLOGY & TOPOGRAPHIC ANALYSIS LABORATORY
BRAT

Search this site

BRAT Resources
- BRAT
- Vision
- Documentation
  - Manual Implementation of Capacity Models
- Escalante Pilot Project
- Beaver Restoration Information
- © 2013 Copyright & Disclaimers

Other Links
- joewheaton.org
- Ecogeomorphology & Topographic Analysis Lab

BRAT > Documentation > Manual Implementation of Capacity Models > Beaver Dam Capacity Model >

1. Input Data

The beaver capacity model requires:

- A drainage network layer
- Some hydrography data tied to that layer
- Vegetation type (by species) raster data
- Digital Elevation Model (DEM)
- Baseflow information throughout drainage network
- Highflow information throughout drainage network

Existing, readily and freely available GIS datasets from GIS data clearinghouses can be used as model inputs. For the pilot study and the Base-BRAT, we used:

- NHD+ for a *drainage network layer & hydrography data*
  - National Hydrography Dataset (NHD) Plus
  - Download both `stream` and `water body` data
- Landfire for *Vegetation Type raster data*
  - Download both `Us_110evt` (existing vegetation type) and `us_110bps` (potential vegetation type)
- USGS Digital Elevation (DEM) data *for Digital Elevation Model (DEM)*
  - Download USGS NED 30 m or 10 m DEM data
- USGS StreamStats for:
  - *Baseflow information (e.g. PQ80 for month with lowest flows)*
  - *Highflow information (e.g. Q2 - 2 year recurrence interval peak flow)*

GIS Tutorial Data

All the input GIS data used for both the beaver dam-building capacity model and the ungulate utilization model for the Escalante River Watershed pilot project is stored in a folder named Input. Input data that we used in the pilot study can be found in Input.zip. The shapefiles and grids are structured into different sub-folders based on the data type. For example, all NHD derived data is in a folder called NHD. For your convenience and as an instruction aid all the shapefiles and grids that were generated during the steps outlined in this manual are included in a folder called Processing. Here is a link: Processing.zip and the final data layer are stored in a folder called Output. Here is a link: Output.zip. Note: each folder also has a READme.doc that describes the contents of that folder.

All the FIS data used in this pilot study is stored in a folder name `BRAT_FIS`. The `BRAT_FIS` folder is divided into two sub-folders BeaverCapacity_FIS and GrazingCapacity_FIS. Input and output .csv tables are stored in the BeaverCapacity_FIS folder and input and output ASCII grids (.asc files) are stored in the GrazingCapacity_FIS folder. Here are links to these data: BeaverCapacity_FIS.zip & GrazingCapacity_FIS.zip

Advance to Step 2 ->

Figure 31 – Screenshot of BRAT website where all GIS deliverables associated with this project can be found.

REFERENCES

Adriaenssens, V., Baets, B.D., Goethals, P.L.M. and Pauw, N.D., 2003. Fuzzy rule-based models for decision support in ecosystem management. Science of the Total Environment, 319(1-3): 1-12.

Albert, S. and Trimble, T., 2000. Beavers are partners in riparian restoration on the Zuni Indian Reservation. Ecological Restoration, 18(2): 87-92.

Allen, A., 1983. Habitat suitability index models: Beaver, US Fish and Wildlife Service, Fort Collins, CO.

Andersen, D.C. and Shafroth, P.B., 2010. Beaver dams, hydrological thresholds, and controlled floods as a management tool in a desert riverine ecosystem, Bill Williams River, Arizona. Ecohydrology, 3(3): 325-338. DOI: 10.1002/eco.113.

Andersen, D.C., Shafroth, P.B., Pritekel, C.M. and O'Neill, M.W., 2011. Managed flood effects on beaver pond habitat in a desert riverine ecosystem, Bill Williams River, Arizona USA. Wetlands, 31(2): 195-206. DOI: 10.1007/s13157-011-0154-y.

Atwater, M.M., 1940. South Fork (Montana) beaver survey. Journal of Wildlife Management, 4: 100-103.

Baker, B.W., Ducharme, H.C., Mitchell, D.C.S., Stanley, T.R. and Peinetti, H.R., 2005. Interaction of beaver and elk herbivory reduces standing crop of willow. Ecological Applications, 15(1): 110-118.

Barnes, D.M. and Mallik, A.U., 1996. Use of woody plants in construction of beaver dams in northern Ontario. Canadian Journal of Zoology-Revue Canadienne De Zoologie, 74(9): 1781-1786.

Barnes, D.M. and Mallik, A.U., 1997. Habitat factors iInfluencing beaver dam establishment in a Northern Ontario watershed. The Journal of wildlife management, 61(4): 1371-1377.

Barnes, D.M. and Mallik, A.U., 2001. Effects of Beaver, Castor canadensis, herbivory on streamside vegetation in a northern Ontario watershed. Canadian Field-Naturalist, 115(1): 9-21.

Bartel, R.A., Haddad, N.M. and Wright, J.P., 2010. Ecosystem engineers maintain a rare species of butterfly and increase plant diversity. Oikos, 119(5): 883-890.

Beier, P. and Barrett, R.H., 1987. Beaver habitat use and impact in Truckee River basin, California. The Journal of Wildlife Management: 51 (4): 794-799.

Belsky, A.J.M.A. and Uselman, S., 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation, 54: 419-431.

Beschta, R.L., 2003. Cottonwoods, elk, and wolves in the Lamar Valley of Yellowstone National Park. Ecological Applications, 13(5): 1295-1309.

Boyce, M.S., 1981. Habitat ecology of an unexploited population of beavers in interior Alaska. In: J.A. Chapman and D. Pursley (Editors), Worldwide Furbearer Conf. Proc. Vol. I. , pp. 155-186.

Braatne, J.H., Rood, S.B. and Heilman., P.E., 1996. Life history, ecology, and conservation of riparian cottonwoods in North America. In: R.F. Stettler, J. H. D.Bradshaw, P.E. Heilman and T.M. Hinkley (Editors), Biology of Populus and its Implications for Management and Conservation. National Research Council, Ottawa, Ontario, Canada, pp. 57-85.

Buckley, M., Souhlas, T., Niemi, E., Warren, E. and Reich, S., 2011. The Economic Value of Beaver Ecosystem Services: Escalante River Basin, Utah, ECO Northwest, Eugene, OR.

Buech, R.R., 1985. Beaver in water impoundments: understanding a problem of water-level management, DM Knighton, Comp., Water Impoundments for Wildlife: A habitat Management Workshop (General Technical Report NC-100). US Department of Agriculture, Forest Service, pp. 95-105.

Burchsted, D., Daniels, M., Thorson, R. and Vokoun, J., 2010. The River discontinuum: applying beaver modifications to baseline conditions for restoration of forested headwaters. Bioscience, 60(11): 908-922. DOI: 10.1525/bio.2010.60.11.7.

Case, R.L. and Kauffman, J.B., 1997. Wild ungulate influences on the recovery of willows, black cottonwood, and thin-leafed alder following the cessation of cattle grazing in northeastern Oregon. Northwest Science, 71: 115-126.

Christensen, J. and Bauer, S., 2005. Escalante River Watershed Water Quality Management Plan, Division of Water Quality, Utah Dept Environmental Quality, Salt Lake City, Utah.

Clayton, S.R., 1996. Factors influencing black cottonwood (Populus trichocarpa) recruitment on the upper Clark Fork River, western Montana, University of Montana, Missoula, Montana.

Demmer, R. and Beschta, R.L., 2008. Recent history (1988-2004) of beaver dams along Bridge Creek in Central Oregon. Northwest Science, 82(4): 309-318. DOI: 10.3955/0029-344X-82.4.309.

Denney, R.N., 1952. A summary of North American beaver management, 1946-1948, 28. Colorado Game and Fish Dept.

Emme, T.J. and Jellison., B.A., 2004. Managing for Beaver on the Bighorn National Forest, Wyoming Game and Fish Department.

Fleischner, T.L., 1994. Ecological costs of livestock grazing in Western North America. Conservation Biology, 8(3): 629-644.

Ganskopp, D. and Vavra, M., 1987. Slope use by cattle, feral horses, deer, and bighorn sheep Northwest Science, 61: 74-81.

Gurnell, A.M., 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography, 22(2): 167-189.

Hall, J.G., 1970. Willow and aspen in the ecology of beaver in Sagehen Creek, California. Ecology, 41(3): 484-494.

Heilman, P.E., 1996. Ecology and watershed functions of western cottonwoods, Natural Resource News Special Edition. Eastern Oregon State College, La Grande, Oregon, USA, pp. 3-5.

Holechek, J.L., 1988. An approach for setting the stocking rate. Rangelands, 10(1988): 10-14.

Hood, G. and Bayley, S., 2008a. Beaver (Castor canadensis) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada. Biological Conservation, 141(2): 556-567. DOI: 10.1016/j.biocon.2007.12.003.

Hood, G.A., 2011. The Beaver Manifesto. Rocky Mountain Books, Toranto, Canada, 130 pp.

Hood, G.A. and Bayley, S.E., 2008b. The effects of high ungulate densities on foraging choices by beaver (Castor canadensis) in the mixed-wood boreal forest. Canadian Journal of Zoology-Revue Canadienne De Zoologie, 86(6): 484-496. DOI: Doi 10.1139/Z08-029.

Hough-Snee, N., Roper, B.B., Wheaton, J.M., Budy, P. and Lokteff, R.L., In Review. Riparian vegetation Communities change rapidly following passive restoration at a Northern Utah stream. Ecological Engineering.

Howard, R.J. and Larson, J.S., 1985. A stream habitat classification system for beaver. The Journal of wildlife management, 49(1): 19-25.

Jang, J.S.R. and Gulley, N., 2009. Fuzzy Logic Toolbox 2: User Guide, Matlab, Matlab, Natick, MA.

Jarerna, I.J., 2006. The abundance and distribution of beavers (Castor Canadensis) in Québec, McGill University, Montréal, Canada.

Jenkins, S.H., 1980. A size-distance relation in food selection by beavers. Ecology, 61(4): 740-746.

Kauffman, J.B., Krueger, W.C. and Varva, M., 1983. Effects of late season cattle grazing on riparian plant communities. Journal of Range Management, 36(6): 685-691.

Kenney, T.A., Wilkowske, C.D., Wright, S.J., 2008. Methods for Estimating Magnitude and Frequency of Peak Flows for Natural Streams in Utah, U.S. Geological Survey, Salt Lake City, UT.

Klir, G.J. and Yuan, B., 1995. Fuzzy Sets and Fuzzy Logic: Theory and Applications. Prentice Hall, Upper Saddle River, New Jersey, 574 pp.

LANDFIRE, 2013. LANDFIRE : LANDFIRE 1.1.0 Vegetation. U.S. Department of Interior, Geological Survey.

Leclerc, M., 2005a. The ecohydraulics paradigm shift: IAHR enters a new era. Journal of Hydraulic Research, 43(4): 63-64.

Leclerc, M., 2005b. Ecohydraulics: A New Interdisciplinary Frontier for CFD. Computational Fluid Dynamics. John Wiley & Sons, Ltd, 429-460 pp.

Lokteff, R.L., Roper, B. and Wheaton, J., 2013. Trout Passage of Beaver Dams in Two Northern Utah Tributaries. Transactions of American Fisheries Society: (accepted).

Macdonald, D.W., Tattersall, F.H., Brown, E.D. and Balharry, D., 1995. Reintroducing the European beaver to Britain: nostalgic meddling or restoring biodiversity? Mammal Review, 25(4): 161-200.

Macfarlane, W.W., Logan, J.A. and Kern, W., 2013. An innovative aerial assessment of Greater Yellowstone Ecosystem mountain pine beetle-caused whitebark pine mortality. Ecological Applications: 23:421-437. DOI: 10.1890/11-1982.1.

McColley, S.D., Tyers, D.B. and Sowell, B.F., 2011. Aspen and Willow Restoration Using Beaver on the Northern Yellowstone Winter Range. Restoration Ecology: no-no. DOI: 10.1111/j.1526-100X.2011.00792.x.

McKay, L. et al., 2012. NHDPlus Version 2: User Guide, U.S. Environmental Protection Agency.

McKinstry, M.C., Caffrey, P. and Anderson, S.H., 2001. The importance of beaver to wetland habitats and waterfowl in Wyoming. Journal of the American Water Resources Association, 37(6): 1571-1577.

Mechanix Illustrated, 1950. Airborne beaver fight floods, Mechanics Illustrated, pp. 147.

Medin, D. and Warren, C., 1991. Small Mammals of a Beaver Pond Ecosystem and Adjacent Riparian Habitat in Idaho, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

Müller-Schwarze, D. and Sun, L., 2003. The Beaver: Natural History of a Wetlands Engineer. Cornell University Press, Ithaca, New York, 190 pp.

Naiman, R.J.,Johnston, C.A and Kelley, J.C., 1988. Alteration of North American streams by beaver. BioScience 28 (11): 753-762

Openshaw, S., 1996. Fuzzy logic as a new scientific paradigm for doing geography. Environment and Planning A, 28(5): 761-768.

Packard, F.M., 1947. A survey of the beaver population of Rocky Mountain National Park, Colorado. Journal of Mammalogy, 28(3): 219-320.

Pasternack, G.B., 2011. 2D Modeling and Ecohydraulic Analysis. Createspace, Seattle, WA, 168 pp.

Pollock, M., Wheaton, J.M., Bouwes, N., Volk, C, Weber, N. and Jordan, C.E., 2012. Working with Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed: Design Rationale and Hypotheses, U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-120, pp.47.

Pollock, M.M., Heim, M. and Werner, D., 2003. Hydrologic and geomorphic effects of beaver dams and their influence on fishes, The Ecology and Management of Wood in World Rivers. 37 (2003):213-233.

Ries, K.G., Steeves, P.A., Coles, J.D., Rea, A.H. and Stewart, D.W., 2005. StreamStats: a US Geological Survey Web Application for Stream Information. US Geological Survey.

Rosell, F., Bozser, O., Collen, P. and Parker, H., 2005. Ecological impact of beavers Castor fiber and Castor canadensis and their ability to modify ecosystems. Mammal Review, 35(3-4): 248-276.

Scheffer, P.M., 1938. The beaver as an upstream engineer. Soil Conservation, 3: 178-181.

Schneider, M. and Jorde, K., 2003. Fuzzy-Rule Based Models for the Evaluation of Fish Habitat Quality and Instream Flow Assessment, Proc. International IFIM Users Workshop, Fort Colins, CO, pp. 22.

Schwab, J.W., 2002. Donna Creek washout-flow: what did we learn? In: P. Jordan and J. Orban (Editors), Terrain Stability and Forest Management in the Interior of British Columbia. Ministry of Forests Science Program, Nelson, BC, Canada, pp. 1-13.

Schwinning, S., Belnap, J., Bowling, D. and Ehleringer, J., 2008. Sensitivity of the Colorado Plateau to change: climate, ecosystems, and society. Ecology and Society, 13(2): 28.

Seager, R., Mingfant Tim, Isaac Held, Yochanan Kushnir, Jian Lu, Gabriel Vecchi, Heuei-Ping Huang, Nili Harnik, Ants Leetmaa, Ngar-Cheung Lau, Chihua Li, Jennifer Velez, and Naomi Nai., 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science Express, 316: 1181-1184.

Senft, R.L., Rittenhouse, L.R. and Woodmanse, R.G., 1985. Factors influencing patterns of cattle grazing behavior on shortgrass steppe. Journal of Range Management, 38(1985): 82-87.

Slough, B.G. and Sadleir, R.M.F.S., 1977. A land capability classification system for beaver (*Castor canadensis* Kuhl). Canadian Journal Zoology., 55: 1324-1335.

Stevens, C., Paszkowski, C. and Foote, A., 2007. Beaver (Castor canadensis) as a surrogate species for conserving anuran amphibians on boreal streams in Alberta, Canada. Biological Conservation, 134(1): 1-13. DOI: 10.1016/j.biocon.2006.07.017.

USGS, 1999. National Elevation Dataset, U.S. Geological Survey.

Warren, E.R., 1927. The beaver: Its work and its ways. Williams & Wilkins.

Westbrook, C., Cooper, D. and Baker, B., 2006. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. Water Resources Research, 42.

Wheaton, J.M., Bennett, S., Bouwes, N. and Camp, R., 2012. Cheap and Cheerful Stream Restoration? An Example of System Wide Woody Addition Treatment, Fall Meeting AGU. EOS Transactions, San Francisco, CA.

Whitham, T.G., K. D. Floate, G. D. Martinsen, E. M. Driebe, and P. Keim., 1996. Ecological and evolutionary implications of hybridization: Populus–herbivore interactions. In: R.F. Stettler, J. H. D. Bradshaw, P.E. Heilman and T.M. Hinckle (Editors), Biology of Populus and Its Implications for Management and Conservation. NRC Research Press, Ottawa, Ontario, Canada, pp. 247–275.

Wilkowske, C.D., Kenney, T.A. and Wright, S.J., 2008. Methods for estimating monthly and annual streamflow statistics at ungaged sites in Utah, U.S. Geological Survey, Salt Lake City, UT.

Williams, R.M., 1965. Beaver habitat and management. Idaho Wildlife Review, 17(4): 3-7.

Wolf, E.C., Cooper, D.J. and Hobbs, N.T., 2007. Hydrologic regime and herbivory stabilize an alternative state in Yellowstone National Park. Ecological Applications, 17(6): 1572-1587.

Woods, A.J. et al., 2001. Ecoregions of Utah (color poster with maps descriptive text, summary tables, and photography), U.S. Geological Survey, Reston, Va.

Worthy, M., 2005. High-resolution total stream power estimates for the cotter river, Namadgi National Park, Australian capital territory, Regolith 2005 - Ten Years of the Centre for Resource and Environment Studies. Australian National University, Canberra, Australia, pp. 338-343.

Wright, J., Jones, C. and Flecker, A., 2002. An ecosystem engineer, the beaver, increases species richness at the landscape scale. Oecologia, 132(1): 96-101. DOI: 10.1007/s00442-002-0929-1.

Zadeh, L.A., 1996. Fuzzy Logic = Computing with Words. IEEE Transactions on Fuzzy Systems, 4(2): 103-111.

Ziv, Y., 1998. The effect of habitat heterogeneity on species diversity patterns: a community-level approach using an object-oriented landscape simulation model (SHALOM). Ecological Modeling, 111(2–3): 135-170. DOI: http://dx.doi.org/10.1016/S0304-3800(98)00096-9.