BEAVER (*CASTOR CANADENSIS*) IMPACT ON WATER RESOURCES IN THE JEMEZ WATERSHED, NEW MEXICO

FINAL REPORT

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SIGNATURE PAGE

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The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

John Melack

April 30, 2014

ABSTRACT

Beaver are known for their engineering abilities that impact the hydrology and ecology of stream systems. Water is a valuable resource in the arid southwest; thus the focus of this study was to evaluate the impact of beaver re-establishment on the water resources of the Jemez Watershed of New Mexico for future statewide management planning. The Beaver Restoration Assessment Tool (BRAT) was used to evaluate the current capacity of the watershed to support beaver based on vegetation, baseflow, and flood stream power. The model demonstrated that the watershed is capable of supporting a re-established beaver population and identified the reaches suitable for dam construction. A hydrological model, the Army Corps of Engineers' Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), was used to determine the hydrologic response of the Jemez River to precipitation. After calibration of the model to the Jemez River discharge, 42 reservoir elements were added to the Rio de las Vacas sub-basin to simulate an initial re-established beaver population The results indicated an attenuation of peak flows by 5 to 30% and an increase in baseflow of 5 to 15% for water year 2011. Additionally, the increase in aquatic and riparian habitat due to dam construction and pond formation was calculated. Finally, it was determined that 15 special status species in the watershed could benefit from beaver activity and habitat creation. Specifically, the Rio Grande cutthroat trout and the New Mexico meadow jumping mouse have the potential to utilize beaver ponds and associated riparian zones as habitat in order to expand their range into stream reaches where they are currently extirpated.

Key Words: beaver, beaver dams, Beaver Restoration Assessment Tool (BRAT), hydrological modeling, HEC-HMS, ecosystems, New Mexico meadow jumping mouse, Rio Grande cutthroat trout, Jemez Watershed, New Mexico

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Background and Significance

This project evaluates how the re-establishment of the North American beaver (*Castor canadensis*) impacts water resources in the Jemez Watershed, New Mexico. This project was proposed by WildEarth Guardians as part of their efforts to re-establish beaver populations in New Mexico and promote the conservation of valuable habitat. WildEarth Guardians' initial interest in the project was to investigate how dam building activity may affect the availability of water in the arid southwest. One possible mechanism is that water trapped behind beaver dams will increase groundwater recharge and, therefore baseflow, which would extend the flow of water into the dry summer.

Objectives

Three objectives were addressed in this project: 1) evaluate the capacity of the Jemez Watershed to support beaver and quantify their dam building activities; 2) model the effect of beaver dams on the flow and timing of the Jemez River; and 3) assess the ecosystem implications of beaver re-establishment for aquatic and riparian habitat that holds the potential to support special-status species in the Jemez Watershed.

Literature Review

The group conducted a review of available literature regarding beaver habitat, impacts of beaver dams on geomorphology, hydrology, and ecology, relevant hydrologic models, availability of data, and special-status species within the watershed. At the conclusion of the literature review, the group determined that beaver dam building activity does have a distinct and measurable effect on the local hydrology. Dams built from riparian vegetation impair the flow of perennial stream systems, which leads to the creation of beaver ponds. These ponds are formed from the attenuation of water. This provides aquatic habitat for beaver populations as well as developing riparian habitat as more of the surrounding area is inundated. These alternations in the stream network contribute to changes in the geomorphology of the system, such as channel incising or rerouting. These effects impact the local ecology by shifting habitat regimes and water availability. Beaver have the ability to alter its environment through its dam building activity, which makes hydrological impacts in the Jemez Watershed due to population re-establishment plausible.

Technical Approach

Beaver Capacity Evaluation

The Beaver Restoration Assessment Tool (BRAT) was used to evaluate the potential for the Jemez Watershed to support a population of re-established beaver and determine how many dams these beavers could build. BRAT analyzed several characteristics of the watershed, including vegetation, stream power, and flood stream power, and output a predicted density of beaver dams on reaches within it. At maximum model capacity, it showed potential for the Jemez to support a re-established beaver population, with dam building predictions of 2-3 dams per 250 meter stream reach being most frequently observed. However, the hydrologic modeling objective relied on the ability to determine the dam building activities of beaver in the Jemez as they are re-established. Thus, the outputs from BRAT were further analyzed at an estimated re-establishment capacity (10% of maximum). At this capacity, 80% of the watershed showed no predicted dam building activities, and the remaining 20% projected 1 dam per 250 meter stream reach. The results – dam count and location – of the BRAT model at re-establishment capacity were used as inputs to the hydrological model and the ecosystem assessment.

Hydrologic Modeling

The US Army Corps of Engineers HEC-HMS model was used to determine the effects of beaver dams on stream flow in the Jemez Watershed. This model calculated annual stream flow in the watershed using spatially distributed time-series precipitation data as an input. The model then calculated fluxes of water between water intercepted by vegetation, water stored on the surface, two groundwater layers and a stream network to produce an annual hydrograph. Water flowed out of each sub-basin through the model's stream network and junctions combined inflow from two streams to one downstream reach. The model was calibrated using a stream gauge located at the watershed outlet. Then, 42 simulated beaver dams were added in the northwest corner of the watershed within the Rio de las Vacas sub-basin. These 42 dams were placed along the stream reach using the BRAT output that represented the chosen re-establishment capacity (10% of maximum capacity). The model was then run twice, once without the beaver dams and once with the beaver dams, to create a 'no dam' scenario and a 'dam' scenario for the 2012 water year. These two scenarios were then compared using the computed hydrograph at a stream junction immediately downstream of the Rio de las Vacas study area. Two climate scenarios were run to determine how the beaver dams affected flow in a wetter and dryer year by increasing and decreasing the 2012 water year summer precipitation by 25%.

The 'no dam' and 'dam' scenario hydrographs showed distinct differences. Peak flows during spring melt and summer storms were reduced between 5% and 30% and the dams increased flows after these peaks by several cubic feet per second. If either a higher beaver dam capacity, or if modeled dams were even more widespread in the watershed, an increased reduction of peak flow and a larger increase of flow after peak events would be expected.

Ecosystem Assessment

Aquatic and riparian ecosystems of the Jemez Watershed were evaluated to determine how beaver re-establishment would affect habitat suitability for other special-status species. A literature review was conducted to determine the effects of beaver on dryland ecosystems in the American southwest. Literature was consulted to estimate the number of beaver per colony (2.7-6.2 beaver) and the number of dams constructed per colony (2-3 dams). Then the size of pools created by beaver dams were calculated based on predicted dam density scenarios using BRAT. Using this information, a range of increases in aquatic and riparian habitat that would be expected to occur as a result of dam building activities from the re-establishment of beaver was calculated. At maximum capacity, the watershed is estimated to support 1,607-2,413 beaver colonies, or approximately 4,343-14,961 beaver, which would create approximately 72 hectares of aquatic habitat and 103 hectares of riparian habitat.

Based on the calculated increase in aquatic and riparian habitat, the watershed could provide increased habitat for 15 special-status species with the potential to occur in aquatic and riparian habitats. Two species were selected for further analysis: The Rio Grade cutthoat trout (*Oncorhynchus clarki virginalis*) and the New Mexico meadow jumping mouse (*Zapus hudsonius luteus)*. The Rio Grande cutthroat trout is listed as a state-sensitive species by the US Forest Service and once had a wide range throughout the southern Rocky Mountains, including the Jemez Watershed. The trout has been extirpated from much of its range but core populations are still present in two sub-basins within the Jemez Watershed. Dam building activities within these two sub-basins could provide additional habitat for the trout, and the dams themselves would significantly reduce the movement of non-native trout. The New Mexico meadow jumping mouse is listed as a state-endangered and federal candidate species and is known to occur within several reaches of the watershed. The US Fish and Wildlife Service has proposed approximately 55 linear kilometers (km) of critical habitat for the species within the Jemez Watershed where the species is present. Dam building activities would create riparian habitat necessary for species survival and conservation.

Conclusions

The Jemez Watershed can support a population of dam building beaver. Should beaver be re-established in the watershed, dam building activities would augment the flow and timing of the stream network. Dam building activities would increase aquatic and riparian habitats to potentially support special-status species.

Recommendations

First, it is recommended that a field study be conducted to validate the analyses of the beaver capacity evaluation. Although difficult due to the extirpated status of beaver in much of the Jemez Watershed, possible studies could investigate historical records or clues of the past presence of beaver dam building activities. In addition, the BRAT model could be modified to explore climate or fire regime scenarios where vegetation inputs are shifted, specifically to reflect poorer suitability for beaver in parts of the watershed.

In order to more comprehensively investigate the impacts of beaver reintroduction to water resources in the Jemez Watershed, hydrologic modeling could be used to investigate a variety of different scenarios including climate, range of beaver establishment, and varying dam characteristics. These simulations could provide insight to statewide beaver management in terms of water resources planning.

To fully analyze how a re-established beaver population would impact the Jemez Watershed ecosystem, the assessment should be expanded to investigate further specific impact on habitat creation from beaver dam building and pond formation and also habitat loss from beaver foraging for food and lumber for dam construction. Additionally, the species evaluation should be expanded to cover all 15 special-status species with the potential to occur in aquatic and riparian habitat within the Jemez Watershed. The potential for beaver to create habitat for special-status species may present conservation planning and compensatory mitigation opportunities.

Based on the results of this project, it is recommended that beaver populations be considered for re-establishment in the Jemez Watershed. This issue is particularly timely as State Senators Tim Keller and Bobby Gonzales introduced State Memorial 4 to the New Mexico legislature to establish a statewide beaver management plan. This piece of legislation was passed by the state Senate on February 19, 2014. The findings from this project may provide information that could be integrated into this beaver management plan.

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°C	degree Celsius
%	percent
ACOE	United States Army Corps of Engineers
ATI	Antecedent Temperature Index
AWC	available water capacity
Bison-M	Biota Information System of New Mexico
BRAT	Beaver Restoration Assessment Tool
cfs	cubic feet per second
DEM	Digital Elevation Model
dss	data storage system
ESRI	Environmental Systems Research Institute, Inc.
ET	evapotranspiration
ft	feet
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System
in	inch
J1552	Junction 1552
kg	kilogram
km	kilometer
LANDFIRE	Landscape Fire and Resource Management Planning Tools Project
LL	Liquid Limit
m	meters
mi	miles
mm	millimeters
MCS	max canopy storage
MGP	maximum groundwater percolation
MGS	maximum groundwater storage
MSI	maximum soil infiltration
MSP	maximum soil percolation
MSS	maximum soil storage
MSTS	maximum soil tension storage
NAD	North American Datum
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resource Conservation Service
PIS	percent impervious surface
RCC	Regional Climate Center
RHESSys	Regional Hydro-Ecologic Simulation System
s	second
SBD	soil bulk density

SC	storage coefficient
sd	standard deviation
SMA	Soil Moisture Accounting
SP	soil permeability
ST	soil thickness
STATSGO	State Soil Geographic Database
TC	time of concentration
USFS	United States Forest Service
USGS	United States Geological Survey
USFWS	United States Fish and Wildlife Service
UTM	Universal Transverse Mercator
VCPN	Valles Caldera National Preserve
WEAP	Water Evaluation and Planning System
WRCC	Western Regional Climate Center

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1.0 BACKGROUND AND PROJECT OBJECTIVES

1.1 Background

In the arid American southwest, the availability of water resources is an increasing concern (Bird, O'Brien & Petersen, 2011). Droughts and the threat of climate change are compounding a problem caused by expanding human populations in water scarce areas. The mountain snowpack is an important part of the water supply system, as it stores water that falls in winter until it is slowly released later in the year. Drought and climate change may cause precipitation to fall less frequently as snow, changing the availability of water to farmers, ranchers, and urban users. Therefore, resource managers are investigating a suite of mitigation strategies to help buffer against an increasingly scarce water supply. One such strategy is the re-establishment of beaver populations in watersheds of the arid southwest.

Much is known about the ecological engineering abilities of the North American beaver (*Castor canadensis*) (Pollock, Heim & Werner, 2003; Pollock, Pess, Beechie & Montgomery, 2004; Bird et al., 2011; Wild, 2011; Gibson & Olden, 2014). Beaver are large, semi-aquatic rodents that have long been touted as a solution to stream quality issues. Beaver are highly adaptable generalists that can live in a wide variety of environments, provided that they have access to running water and material to build dams. These dams alter the dynamics of the stream and its associated biological space. It is hypothesized that beaver may be able to help mitigate water storage problems. By building dams on lower order streams, beaver have the potential to retard the flow of water from early snowmelt and extend stream flow to later in the year. Beaver are thought to have these effects because their dams can both physically prevent water from flowing and increase groundwater recharge rates.

States such as Washington and Utah have introduced beaver management plans that broadly include the use of beaver as integral to maintaining and re-establishing stream health. Beaver re-establishment has been investigated throughout the Cascade and Rocky Mountain ranges in Washington, Oregon, Utah, and Colorado. State and federal agencies and academic researchers in Utah and Colorado are particularly interested in this group project for incorporation into beaver management planning as an adaptation to climate change, specifically, the Utah Department of Wildlife and the Department of Watershed Science at Utah State University (Utah DWR, 2010).

The state of New Mexico is currently developing a statewide beaver management plan. In light of this, WildEarth Guardians is investigating the potential for beaver to be used in water resource management strategies. As a conservation non-profit organization in New Mexico, WildEarth Guardians is interested in returning beaver to the ecosystem to fulfill their mission of native species restoration. Beaver were historically widespread throughout North America before they were nearly trapped to extinction for their pelts in the early 20th century. Furthermore, farmers and ranchers often considered beaver as pests and actively sought to remove them from their land, a practice that continues to this day.

Should beaver re-establishment prove to both extend stream flow later in the season and help increase mountain water storage, it would provide WildEarth Guardians with a convincing argument to present to stakeholders to support this practice. Reframing the beaver's image from pests to providers of important ecosystem services may convince local landowners to support the re-introduction of beaver into a greater portion of their historic range.

Additional stakeholders within New Mexico are state and federal wildlife agencies, including the New Mexico Department of Game and Fish, the Surface Water Quality Bureau at the New Mexico Environmental Department, US Fish and Wildlife Service, and US Forest Service; and academic researchers at local New Mexico universities, including the Department of Fish, Wildlife, and Conservation Ecology at New Mexico State University. Additional stakeholders include landowners and groups such as Animal Protection of New Mexico who serve to determine safe ways for beaver re-establishment and landowner interaction; farmers; ranchers; anglers; conservation groups; Native Americans; and downstream water users (New Mexico Environment Department, 2013).

1.1.1 Similar Research Projects

WildEarth Guardians was consulted to obtain relevant information and develop a conceptual model of how the project would be conducted. Of principal interest were a series of watershed assessments conducted by the United States Forest Service (USFS) on the Jemez Watershed (USFS, 2001-05). These assessments include information on land use, the various jurisdictional agencies in the region, and suitable beaver habitat. Furthermore, the assessments include maps and watershed delineations of all sub-basins within the Jemez Watershed. Similar work has been performed by Joseph Wheaton and William MacFarlane at Utah State University (MacFarlane & Wheaton, 2013). They constructed a model, the Beaver Restoration Assessment Tool, to determine suitable beaver dam building habitat. The goal of the model is to combine characteristics of a watershed and serve as a framing tool for beaver re-establishment efforts.

Several studies investigated the effects of beaver dams on the hydrology of the stream network. One report investigated the hydrologic impacts of beaver ponds on stream flows on a river in Alaska and provided methods for calculating flood attenuation based on parameters like beaver dam density and average dam height (Beedle, 1991). A study in Belgium was conducted where European beaver (*Caster fiber*) was re-introduced to the Ourthe Orientale basin in Ardennes. This research focused on the hydrologic effects of a series of beaver dams. It was found that there was a significant lowering of discharge peaks downriver of the beaver dams. The study provided evidence that natural measures for flood control were viable in small mountain stream environments (Nyssen, Pontzeele & Billi, 2011). A study in eastern Oregon explored how beaver re-establishment added to the expansion of riparian habitat due to river aggradations (Pollock et al., 2004), particularly as incised channels within a stream network, like those found in semi-arid environments, pose a problem due to potential changes in geomorphologic and hydrologic processes. The key findings of these studies were essential building blocks for this project.

1.2 Project Objectives

1.2.1 Beaver Capacity Evaluation

Objective

Evaluate the capacity of the Jemez Watershed to support a re-established beaver population and determine the quantity and location of the dams these beaver would construct.

Significance

The modeling performed allowed the determination of whether the Jemez River and tributaries could support a population of beaver in its current state. In addition, the location of the dams can be incorporated into the hydrologic model as well as frame and quantify the ecosystem assessment portion of the project.

1.2.2 Hydrologic Modeling

Objective

Estimate the impact of beaver dam on the flow volume and timing of the Jemez River using a hydrologic model.

Significance

The goal of this objective is to determine whether the addition of beaver dam to the Jemez Watershed will have an impact on the flow volume and timing of the Jemez River, and if so, what that impact will be. Given that the Jemez River provides for both human and natural uses, any impact to the river has potentially far-reaching consequences. Therefore, some degree of quantification of change to the magnitude and timing of flow is required for planning. Hydrological modeling can assist in calculating the cumulative effects of complex surfaces and help estimate the impacts of beaver dam to the Jemez River.

1.2.3 Ecosystem Assessment

Objective

Evaluate the effect of dam building beaver on aquatic and riparian ecosystems within the Jemez River and how beaver re-establishment may affect special-status species.

Significance

This objective aims to evaluate the ecological effect of beaver and beaver dams in the Jemez Watershed. The BRAT dam density output allows an estimation of the increase in aquatic and riparian habitat that beaver re-establishment would create. By examining how beaver populations may affect local ecology within the watershed, the group can evaluate how special-status species may benefit from habitat creation. This can allow the group to make inferences on how beaver re-establishment could indirectly affect the watershed's ecosystem in addition to its hydrologic effects.

1.3 Characterization of the Jemez Watershed

1.3.1 Location

The Jemez Watershed is located in north central New Mexico, west of Santa Fe, and north of Albuquerque. The majority of the watershed is located in Sandoval County, with portions in Los Alamos and Rio Arriba Counties. It encompasses the towns of Jemez Springs, Ponderosa, and San Ysidro, in addition to the Jemez Pueblo, Santa Ana Pueblo, and Zia Pueblo (Figure 1.3-A). The watershed covers an area of approximately 2,690 square kilometers (km^2) that drains the western portion of the Jemez Mountains and the Sante Fe National Forest, the Valles Caldera National Preserve (VCPN), and the lower Jemez River Valley. The watershed ranges in elevation from 1,546 meters (m) at the Jemez River Reservoir to 3,435 m at Redondo Peak (Figure 1.3-B).

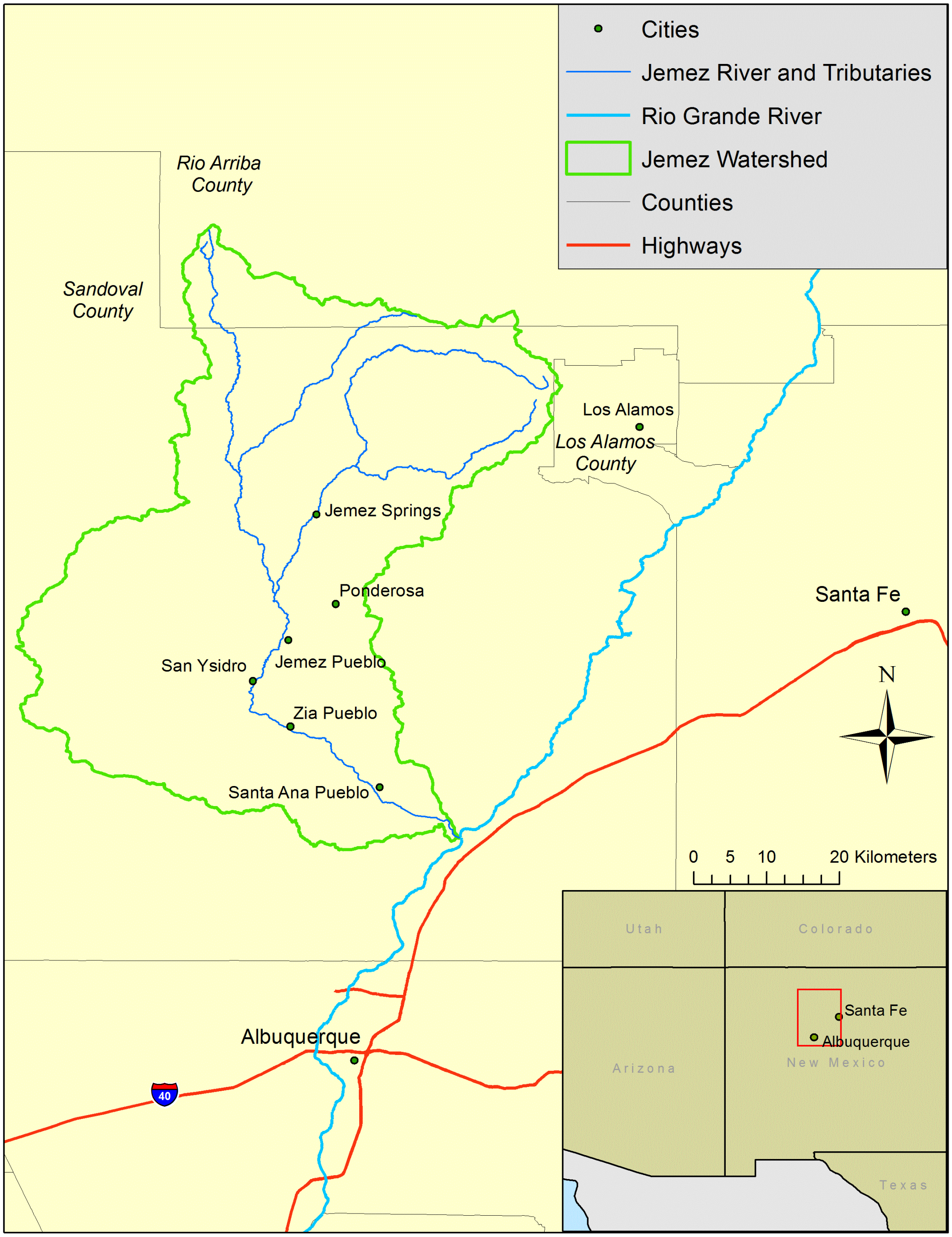

Figure 1.3 - A, Location of the Jemez Watershed

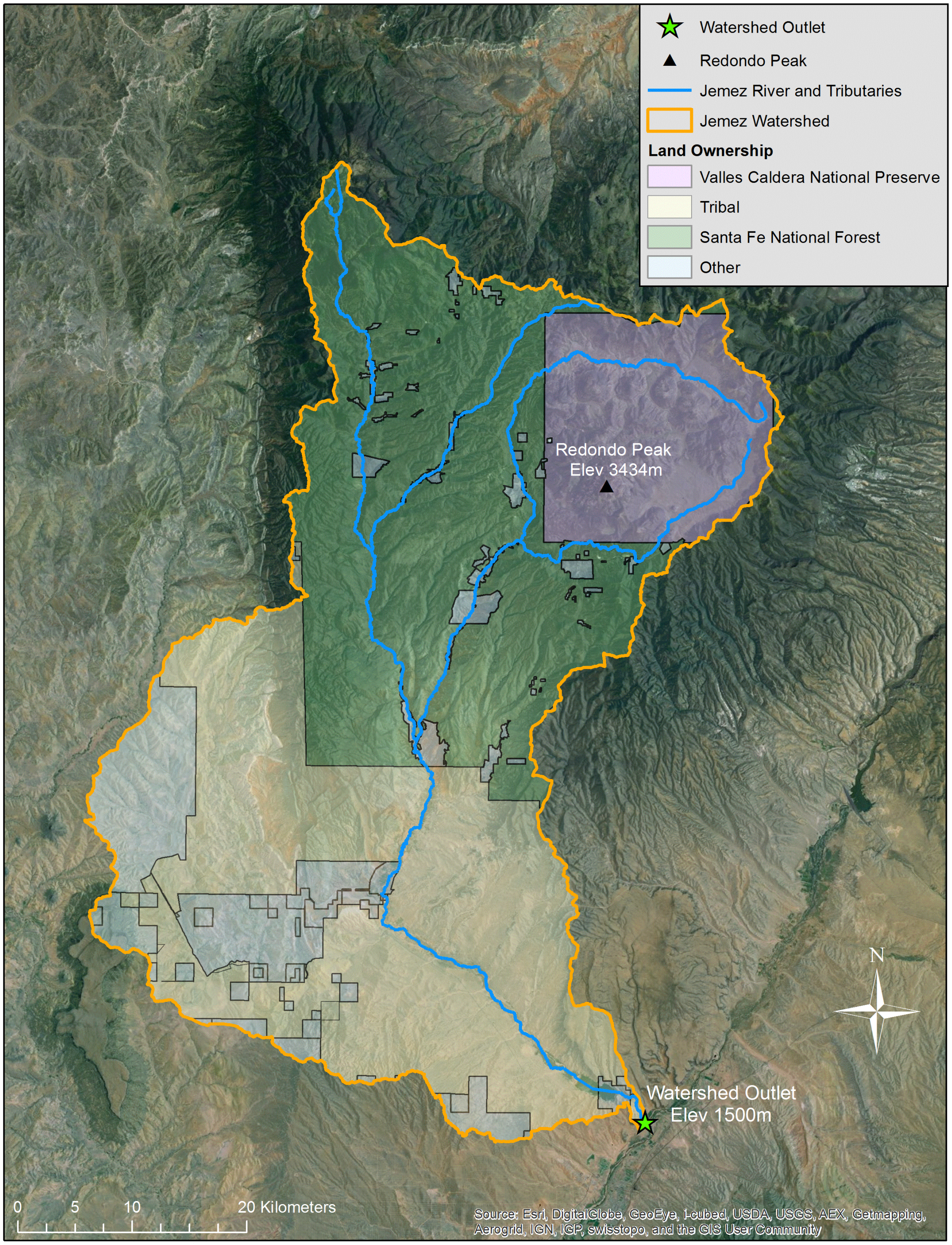

Figure 1.3 - B, Physical Setting

1.3.2 Climate

The Jemez Watershed is located within the Western Mountain Regions Ecoregion (USEPA, 2006). Extensive mountains with nutrient-poor soils characterize this ecoregion. Land cover is primarily forested (59%), and the climate is typically sub-arid to arid in lower regions and humid and cold at higher elevations. The Jemez Watershed averages 550 millimeters (mm) of combined rain and snowfall every year. The watershed experiences monsoonal rainfall, which makes July, August, and September the wettest months of the year. The rain is spatially sporadic, as one storm can drop a large amount of rain in one area and none in nearby areas. The high elevation of the northern part of the watershed causes winter precipitation to fall as snow. Thirteen (13) rain gauges are located throughout the watershed, and these data were collected and used for analysis (Figure 1.3-C). The rain gauge sites include Cebollita Springs, Conejos, Coyote, Headquarters VCNP, Jemez, Jemez Dam, Jemez Springs, Los Posos, Redondo Peak, San Antonio Creek, Tower, Wolf Canyon, and Valle Toledo (WRCC, 2013).

The watershed varies in elevation and ranges in temperature. Temperature data were collected at the same stations used to collect rainfall data (Figure 1.3-C). At Redondo Peak, located at an elevation of 3,231 m, the average summer temperatures range from 7 degrees Celsius (°C) to 20°C, and the average winter temperatures range from -10°C to 0°C. At the town of Jemez Springs, located at an elevation of 2,438 m, the average summer temperatures range from 15°C to 30°C, and the average winter temperatures range from -6°C to 8°C (WRCC, 2013).

Figure 1.3 - C, Rain and Snow Gauge Locations

1.3.3 Geology

There are two different geologic zones within the watershed: the Valles Caldera and the lower Jemez River Valley (Figure 1.3-B). The Valles Caldera is a collapsed magma chamber approximately 22 km across, and incorporates multiple resurgent lava domes that rose following the chamber's collapse around 1.25 million years ago. The rolling topography in the Valles Caldera differs from the nearby Jemez Mountains through which rivers have cut deep, steep-walled valleys. The Jemez Mountains are comprised of primarily volcanic materials, including basalt, basaltic-andesite, rhyolite, pyroclastic flow breccias, and welded tuffs. Valley floors consist of compacted sands and gravels in the form of alluvial fans, river channel deposits, and volcanic rocks preserved in a complex of depressed fault blocks within the Rio Grande depression. Several mesas are capped by basaltic and andesitic lava flows.

1.3.4 Hydrology

The Jemez River is approximately 105 km long and drains an area of approximately 2,690 km2 consisting of the Jemez Mountains, the Santa Fe National Forest, and the Valles Caldera (Figure 1.3-B). Upland tributaries drain into the Jemez River, Rio Guadalupe, Rio Cebolla, San Antonio Creek, and Rio Salado, which follow the topographic gradient and flow towards the south-southeast into the Rio Grande. The Rio de las Vacas sub-basin in the northwest region of the watershed was selected for further analysis (Figure 1.3-D).

1.3.5 Land Ownership and Use

The land within the watershed is mostly federal land under the jurisdictions of multiple agencies (Figure 1.3-E). The USFS manages the Santa Fe National Forest, which makes up the majority of the watershed. The VCNP manages the land within the Valles Caldera. The watershed also includes villages of San Ysidro, Jemez Springs, as well as several tribal areas (Figure 1.3-A).

Land use within the watershed is primarily rangeland and coniferous forest but includes deciduous forest and cropland/pasture (Figure 1.3-F). The majority of the land is under the jurisdiction of the USFS. The USFS balances the needs of many different parties and promotes recreation and conservation, logging, mining, and grazing within the watershed. The VCNP supports scientific research, conservation, restoration, and stewardship project within its jurisdiction. Additionally, the Jemez Watershed is a location for recreational activity in the form of hiking, fishing, and biking.

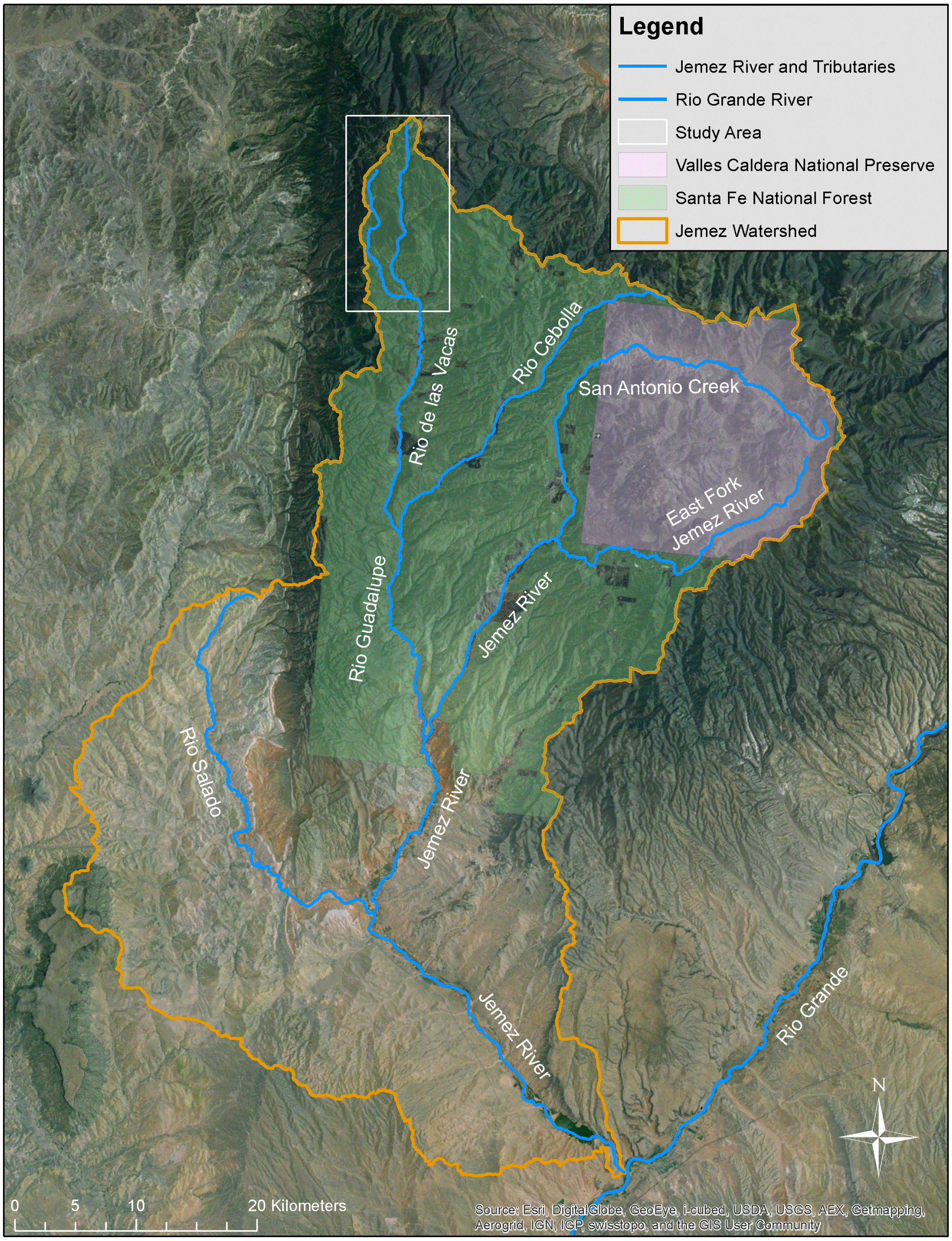

Figure 1.3 - D, Hydrology of the Jemez Watershed

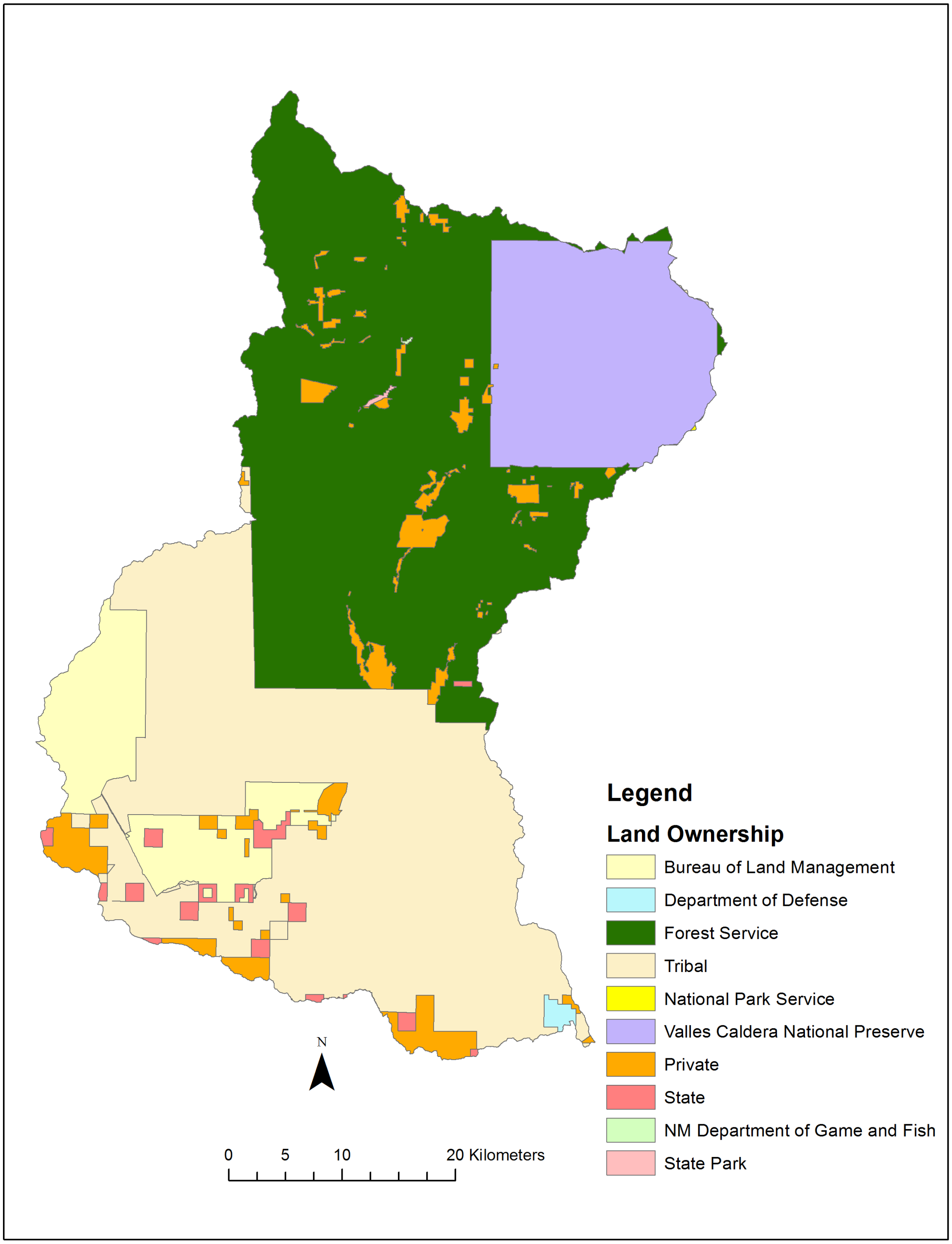

Figure 1.3 - E, Land Ownership

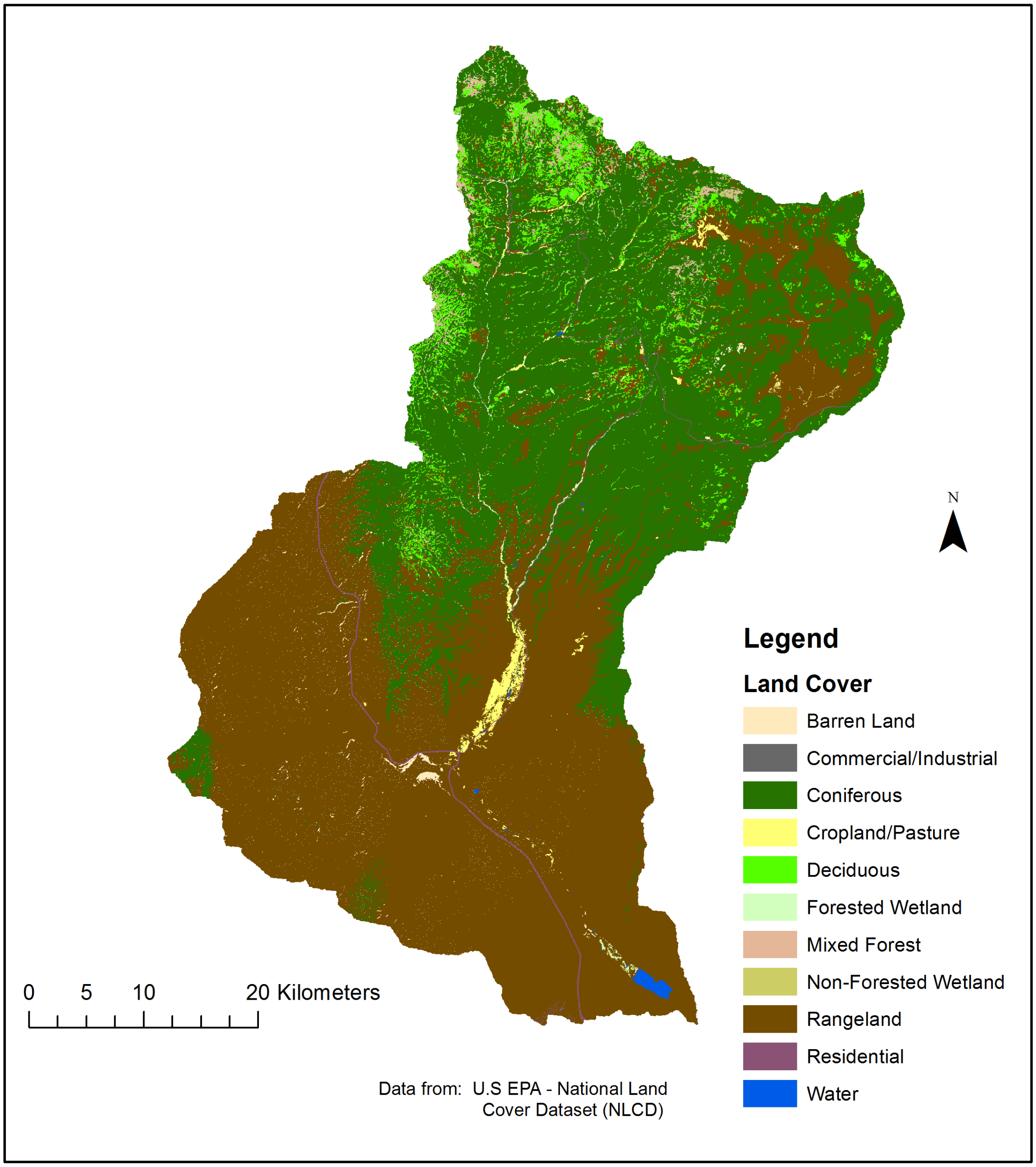

Figure 1.3 - F, Land Use

1.3.6 Known Beaver Locations

Beaver have historically been known to occur throughout North America until heavy trapping practices extirpated them from most of their range (Figure 1.3-G) (Gibson & Olden, 2014). Beaver occur in much of the western United States, particularly in the Rocky, Cascade, and Sierra Nevada Mountain ranges. Within New Mexico, beaver were historically common throughout the state but today can only be found in low densities in disjoint areas. The Department of Fish, Wildlife, and Conservation of New Mexico State University conducted research on existing beaver populations in New Mexico. This research shows that beaver dam sites are sparsely distributed throughout the state. Three such active dams were located within the Jemez Watershed (Frey & Malaney, 2009).

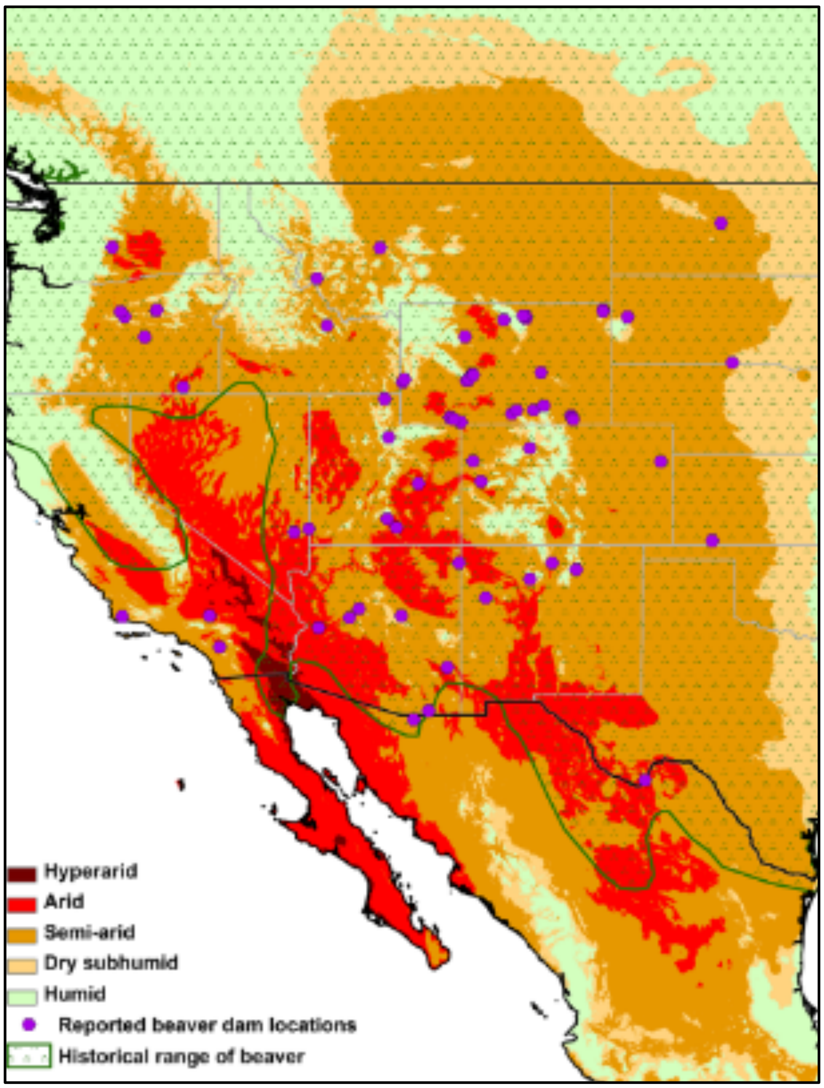

Figure 1.3 - G, Known Beaver Dam Locations
Source: Gibson & Olden, 2014

2.0 BEAVER CAPACITY ASSESSMENT

2.1 Introduction

The basis for analysis of the impacts of beaver on natural resources in the Jemez Watershed rests on the ability to determine the density of beaver dams (dam count per length of stream) in the watershed. Dam counts, rather than beaver counts, were important because estimating beaver population densities is difficult and of less direct consequence to the flow of water systems in a watershed. In addition, validation using traditional or remote sensing methods is simpler when estimating the density of beaver dams. Joseph Wheaton and William MacFarlane developed the Beaver Restoration and Assessment Tool (BRAT) in 2013 to provide a tool for estimating the likelihood of beaver dam building activity in a watershed.

BRAT combines physical characteristics of the watershed to determine the suitability of the environment for supporting dam building. Information on the development of the model and initial application in the Escalante Watershed of Utah can be found on the BRAT web portal at Utah State University (http://brat.joewheaton.org). The model was adaptable to the Jemez Watershed because the information required to build it was readily available from public sources.

2.2 Methods

2.2.1 Model Components

Stream Network

Beaver require reliable perennial water sources to establish a colony and build dams (Beedle, 1991; Nyssen et al., 2011; Gurnell, 1998). Although evidence exists that beaver occasionally use ephemeral water sources (Gurnell, 1998), it is assumed that this is not occurring in the Jemez Watershed. The team acquired the drainage network Geographic Information System (GIS) layer from the National Hydrography Dataset (NHD), and disregarded streams that were not considered perennial by the United States Geological Survey (USGS). In order to generalize results, the analysis required the stream segments to be of equal length, which was set to 250 m. To accomplish this, stream reaches defined by the NHD dataset were combined into one continuous stream feature. Environmental Systems Research Institute Inc.'s (ESRI) ArcGIS tool "construct points", was then used to create points every 250 m along the combined stream feature. Finally, the "split line at points" tool was used to split the line feature into 250 m reaches. Some reaches at the beginning or end of streams were cut into lengths smaller than 250 m due to both error introduced by the ArcGIS tool and the river network not being exactly divisible by 250.

Vegetation

Evidence of wood suitable for dam building by beaver was based on the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) vegetation datasets for the Jemez Watershed. LANDFIRE information is based on classification from Landsat imagery, and was obtained from the LANDFIRE webportal (LANDFIRE, 2013). Vegetation types were classified into suitability categories which ranged from 0 (not suitable) to 4 (ideal) based on categories used in the original run of the BRAT model on the Escalante River, Utah (Figure 2.2-A).

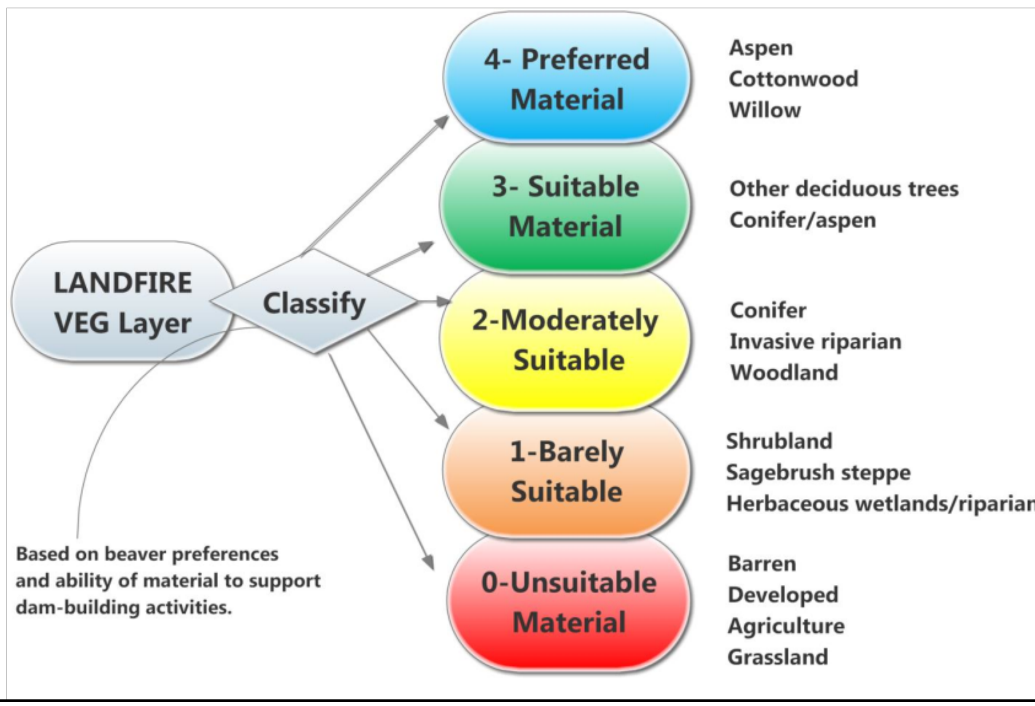

Figure 2.2 - A, BRAT Classification of Vegetation Type in a Watershed
Source: MacFarlane and Wheaton, 2013

Using ArcGIS, these classifications of suitability were applied manually for each of the vegetation types found at the Jemez Watershed. Subsequently, all 30 m pixels from the LANDFIRE imagery of the study site were assigned a suitability value creating a suitability raster layer. The vegetation suitability raster was then reduced to focus on the 30 m and 100 m buffers surrounding the perennial stream segments. These then resulted in a raster where vegetation suitability values could be associated with 250 m segments of perennial streams.

The raster depicting vegetation suitability for each 250 m stream reach was then inputted into the Geospatial Modeling Environment, an add-on to ArcGIS. Using the "intersect lines with raster" tool, the vegetation suitability values were added to the stream reach layer. Each 250 m stream reach within the feature layer was then associated with a vegetation suitability value.

Stream Power

The power of a stream plays an important role in determining the ability of beaver to successfully construct and maintain a dam. The ability of a stream to provide constant access to water is determined by the perennial status of a stream in the NHD dataset as mentioned in the section above. However, even at baseflow a stream may be too powerful to allow beaver to construct their dams or maintain them for a suitable period of time. The BRAT model uses stream power as a physical characteristic of the stream as an input to determine beaver capacity.

The calculation of stream power necessitates inputs of drainage area, slope, and elevation for each 250 m stream reach. These data were prepared using both ArcGIS and the Geospatial Modeling Environment. All three of these inputs were derived from a digital elevation model (DEM), which was obtained from the USGS and clipped to the Jemez Watershed.

The drainage area was calculated through a multistep process. When using a DEM for hydrologic analysis, sinks and imperfections in the DEM can create false values. Therefore, the DEM was corrected using the fill tool in ArcGIS, which removes these sinks from the DEM. Next, a flow direction grid, which determines which direction water would flow out each DEM raster cell, was created. Using the flow direction grid, a flow accumulation grid was created. This grid defines the number of upstream raster cells that would flow into each cell. This flow accumulation grid was used to determine the drainage area in each stream reach.

These data were added to the vegetation buffer layers described in the previous section using the Geospatial Modeling Environment. The "intersect lines with raster" tool was used to input the information from the flow accumulation grid into the stream reach layer, giving the upstream area to each stream reach. The same tool was used to extract elevations from the DEM for each stream reach for use in calculating slope. Slope was calculated using the difference in elevation between the beginning and end of each stream reach and the distance of the stream reach. When the slope was 0, caused by the DEM giving the start and end points of the stream reach the same elevation, a small slope (0.05) was assigned so stream power could be calculated. Stream power, measured in watts, is defined as:

$$\text{Stream Power} = p \cdot g \cdot Q \cdot S \qquad \text{(EQ 1)}$$

Where p is the density of water (assumed to be 1,000 kilogram (kg)/m^3), g is the gravitational constant (9.8 m/second (s)^2), Q is the discharge in studied stream segment

(m^3/s), and S is the slope of the studied stream segment. The discharge for each stream segment was estimated using regional regression equations. These equations are estimated by the USGS from historical stream gauge data in different regions of New Mexico and elsewhere.

Baseflow. The stream power of the Jemez River was calculated at baseflow. The original BRAT documentation states that baseflow for the model is defined as the flow that occurs on at least 80% of the days in the year. This definition was used. The group correlated this definition to available data, namely regression equations derived for low-flow frequency on unregulated streams in New Mexico, developed by the USGS. The regression equations attempt to define discharge at the "4 day, 3 year" (4Q3) low flow, the best approximation of baseflow. Units for the USGS equations are given in American units, and the outputs of the equations are converted to metric within the BRAT model. The regression equation developed for the mountainous regions of New Mexico, appropriate for the Jemez Mountains, is stated as:

$$4Q3 = 7.3287 \cdot 10 - 5\ DA0.7 \cdot Pw3.580 \cdot S1.350 \qquad \text{(EQ 2)}$$

Where $4Q3$ is low flow in feet (ft)^3/s, DA is the drainage area in square miles (mi^2), Pw is the average basin mean winter precipitation from 1961 to 1990, in inches (in), and S is the average basin slope in percent (%). DA is calculated previously in the BRAT pre-processing step for each stream reach. Pw and S were estimated from the same USGS document, as 24.39 in and 0.234 in, respectively. The estimate for 4Q3 was plugged into the stream power equations along with the calculated slope for each segment, and each segment was classified into three dam building suitability categories, based on the original BRAT development. These categories are:

- Can build dam
- Can probably build dam
- Cannot build dam

These categories were used in the rule tables for the Fuzzy Logic Toolbox modeling step (explained in section 2.2.2). Estimates for the generation of these categories were derived during the original analysis for the development of the BRAT model, using known dams and stream powers in several watersheds in Utah, including the Escalante. These estimates were retained as best approximation for the Jemez Watershed.

Flood Stream Power. Similar calculations of stream power were then undertaken to determine the ability of the beaver dams to remain in the streambed during both the 2-year flood (Q_2) and the 25-year flood (Q_{25}). Regression equations developed by the USGS were used as inputs to the model. They are, for Q_2 and Q_{25} respectively, where A is the upstream drainage area in mi^2:

$$Q2 = 1.328 \cdot\ 102 \cdot\ A0.420 \qquad \text{(EQ 3)}$$

$$Q25 = 7.800 \cdot 102 \cdot A0.372 \qquad \text{(EQ 4)}$$

Based on the stream power that results from these calculations, the BRAT model assigns a reach into four additional categories, which are:

- Dam Persists
- Occasional Breach
- Occasional Blowout
- Blowout

2.2.2 MATLAB® Environment

All components of the BRAT model (vegetation, baseflow, and flood stream power) were integrated along with the physical characteristics of each stream reach into MATLAB® and used in the Fuzzy Logic Toolbox. The model intersects established suitability categories and determines the grouped suitability of the habitat for beaver dam building activities. Finally, this was translated into an estimated number of beaver dams for a specific reach. An example of the rule tables used in the BRAT model within MATLAB® is shown in Figure 2.2-B. Output categories were assigned for each reach and are as follows:

- None – No dams
- Occasional – 1 dam
- Frequent – 2 to 3 dams
- Pervasive – 4 to 7 dams

	IF	INPUTS Suitability of Streamside Vegetation		Suitability of Riparian/Upland Vegetation		OUTPUT 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

Figure 2.2 - B, Example of BRAT Rule Table
Source: MacFarlane and Wheaton, 2013

The Jemez Watershed is located in a semi-arid environment and is characterized by strong summer floods and storms. As such, it could be expected that many studied reaches would output a predicted number of dams between 0 and 1 as they would not be ideal for beaver dam building activities. Because of the difference between a reach with no dams and a reach with a dam, outputs that were fractions of 1 could not be simply rounded to 1. Furthermore, the hydrologic modeling objective required a whole number for a dam count in each reach as a suitable input. Therefore, the fraction was used as a probability of being in either category. For example, an output of 0.6 would generate a 60% chance of being a reach with 1 dam, and a 40% chance of being a reach with no dams. This reasoning was expanded to the other output categories (1-2, 2-3, and 4-7).

Finally, outputs were modified to represent conditions in the Jemez Watershed. Because BRAT is a capacity model, the original outputs do not necessarily represent a realistic portrayal of the potential of the watershed to support beaver. It was estimated that an approximation of 30% of maximum capacity would be realistic target for re-establishment goals (J. Wheaton, personal communication, 2013). Thus, model outputs were scaled back to reflect this percentage of capacity. Due to hydrologic modeling limitations the group chose to model beaver dams in the Jemez Watershed at 10% of maximum capacity. This was deemed a reasonable initial goal for both re-establishment efforts and determining beaver impacts on stream hydrology.

2.3 Results

The component parts necessary to run the BRAT model were calculated. The outputs of the stream power calculations can be represented visually to describe the ability of beaver to build dams under certain conditions for reached in the Jemez. The results of the component analyses of the BRAT model show that the capacity for beaver to build dams in the watershed is primarily limited by vegetation (Figure 2.3-A). All perennial streams in the watershed are suitable for dam building at baseflow (Figure 2.3-B), and dams are not expected to be destroyed during 2-year recurrence flood events over the watershed (Figure 2.3-C). The outputs show that a large majority of stream reaches remain most suitable for dam building event during 25-year recurrence floods (Figure 2.3-D). Therefore, vegetation is likely the limiting factor, as many regions in the Jemez Watershed are estimated to have vegetation that is least suitable to beaver and their dams building activities.

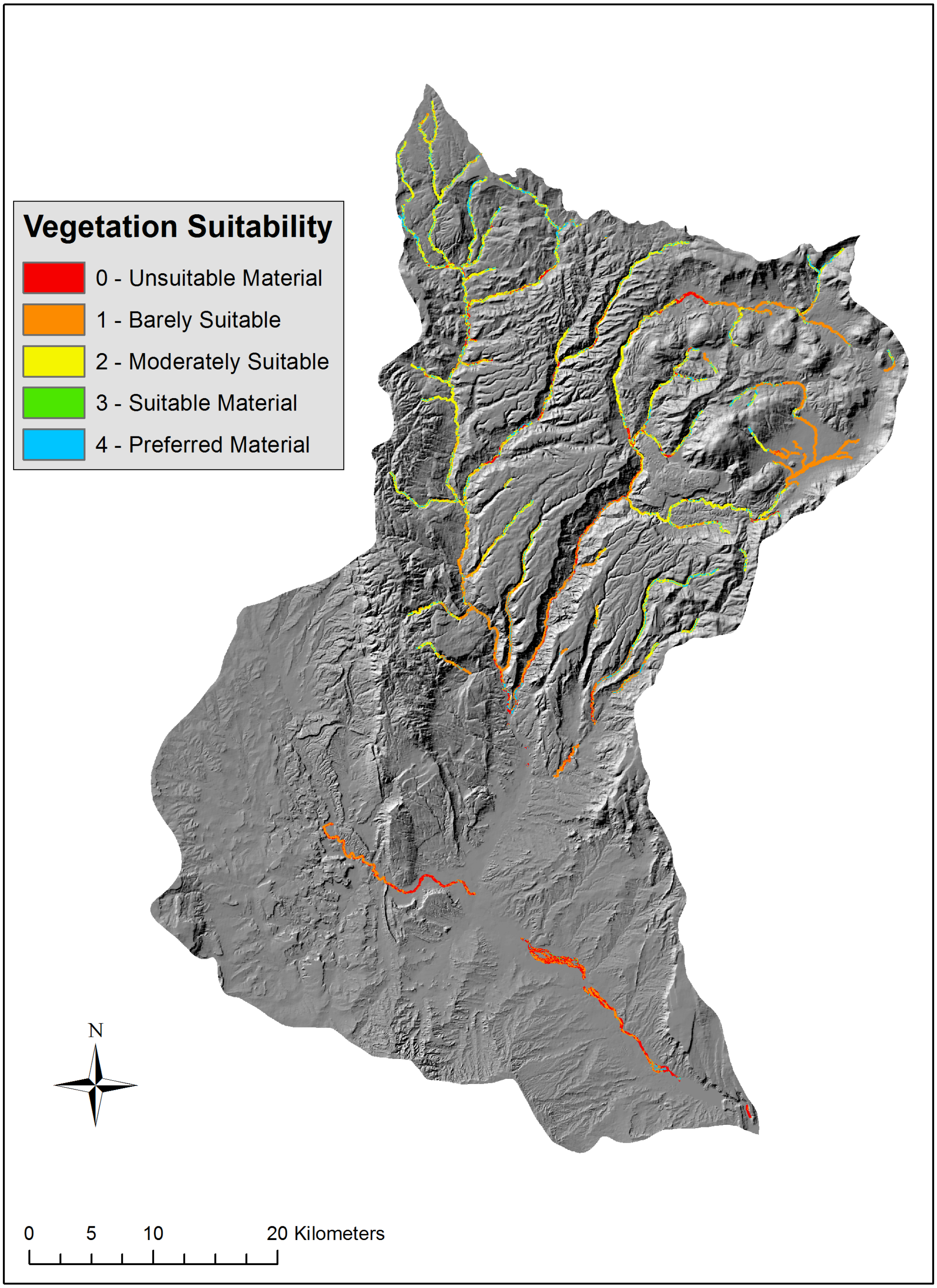

Figure 2.3 - A, BRAT Reach Classification Based on Vegetation Suitability

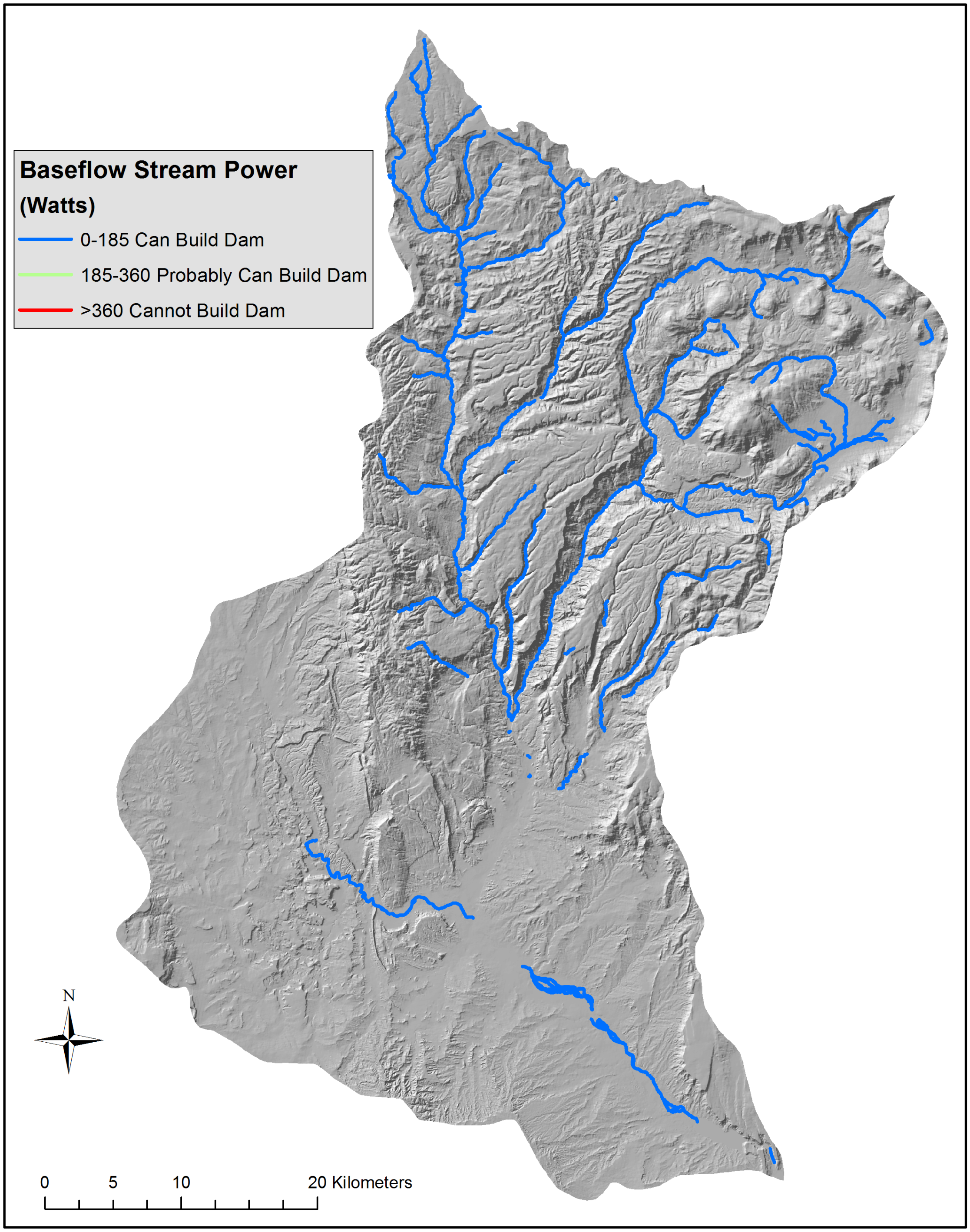

Figure 2.3 - B, BRAT Reach Classification at Baseflow

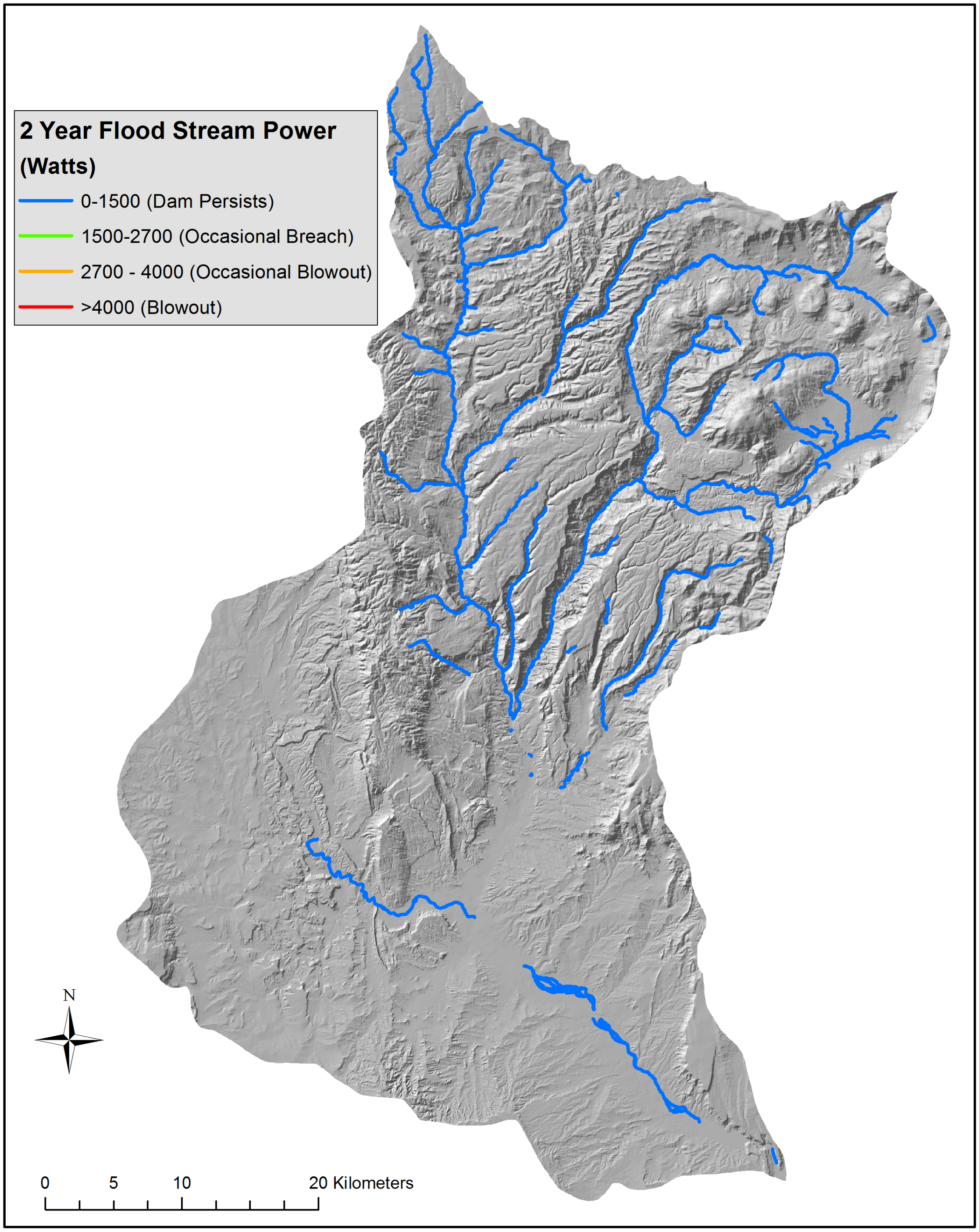

Figure 2.3 - C, BRAT Reach Classification at 2-Year Flood

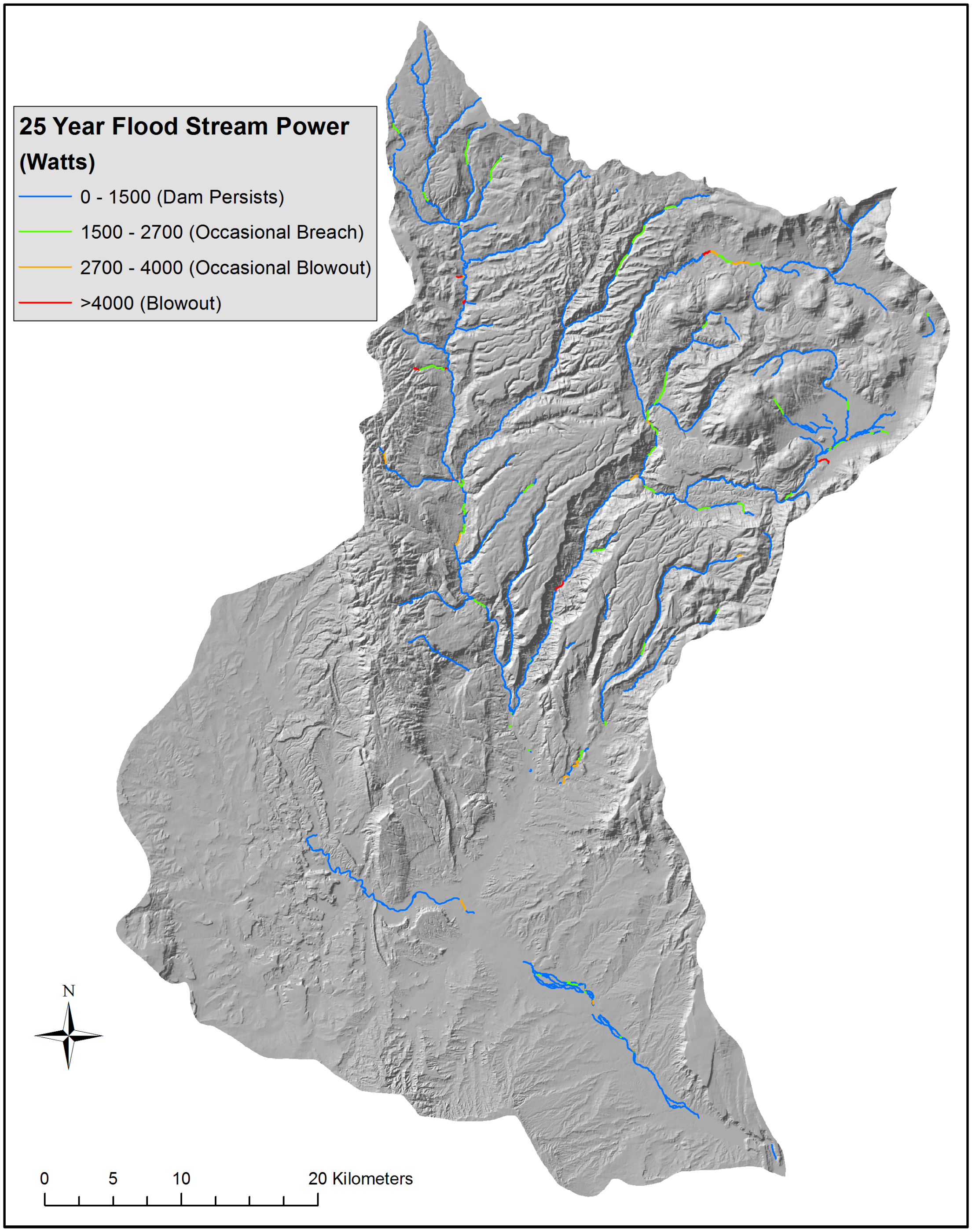

Figure 2.3 - D, BRAT Reach Classification at 25-Year Flood

The model included 2,501 stream reaches under three capacity scenarios: 100% capacity , 30% capacity, and 10% capacity (Table 2.3-A). At full capacity, the greatest number of dams predicted on a reach was 7 (median = 2, mean = 1.9, standard deviation (sd) = 1.4) , whereas this was 4 at 30% capacity (median = 1, mean = 0.59, sd = 0.57), and only 1 at 10% capacity (median = 0, mean = 0.2 sd = 0.4). The statistical distribution of the data is represented in Figure 2.3-E.

Table 2.3 - A, Beaver Dam Density Under Three Capacity Scenarios

Dam Capacity	None (0 dams)		Occasional (1 dam)		Frequent (2 to 3 dams)		Pervasive (4 to 7 dams)	
	Count	%	Count	%	Count	%	Count	%
100%	503	20	559	22	974	38	465	18
30%	1084	43	1368	54	40	<1	9	<1
10%	1990	80	511	20	0	0	0	0

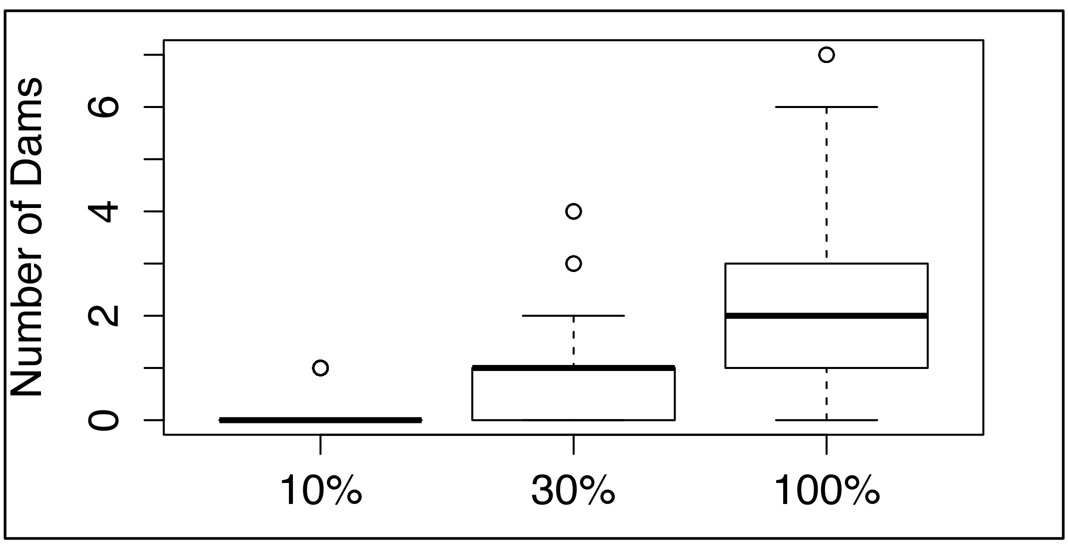

Figure 2.3 - E, Statistical Distribution of Dam Density

Visual representations of the BRAT model run outputs can be seen in Figures 2.3-F, 3.2-G, and 3.2-H). These maps were also converted into a Google Earth product that can be easily shown without sophisticated GIS tools.

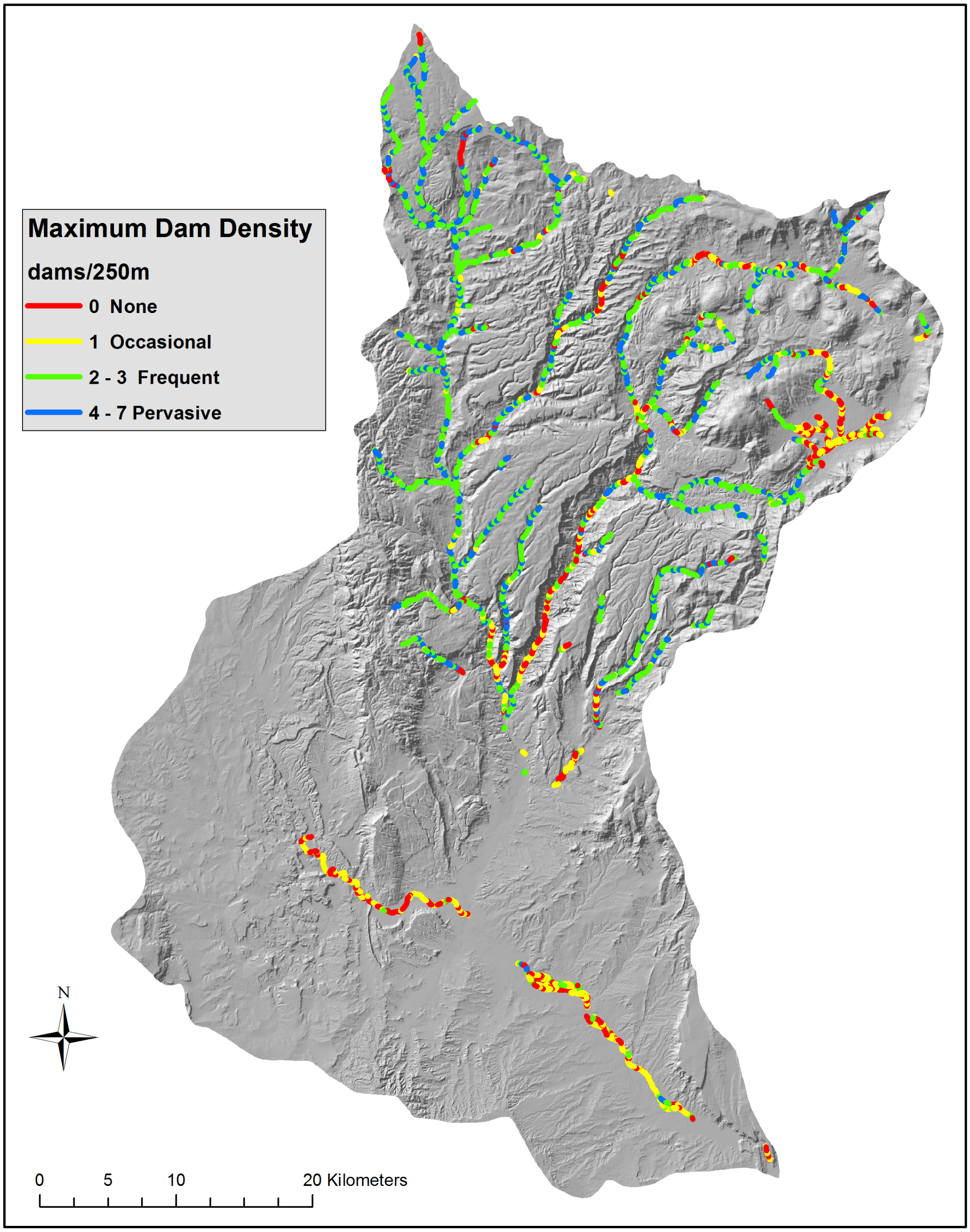

Figure 2.3 - F, BRAT Output Results at 100% Capacity in the Jemez Watershed

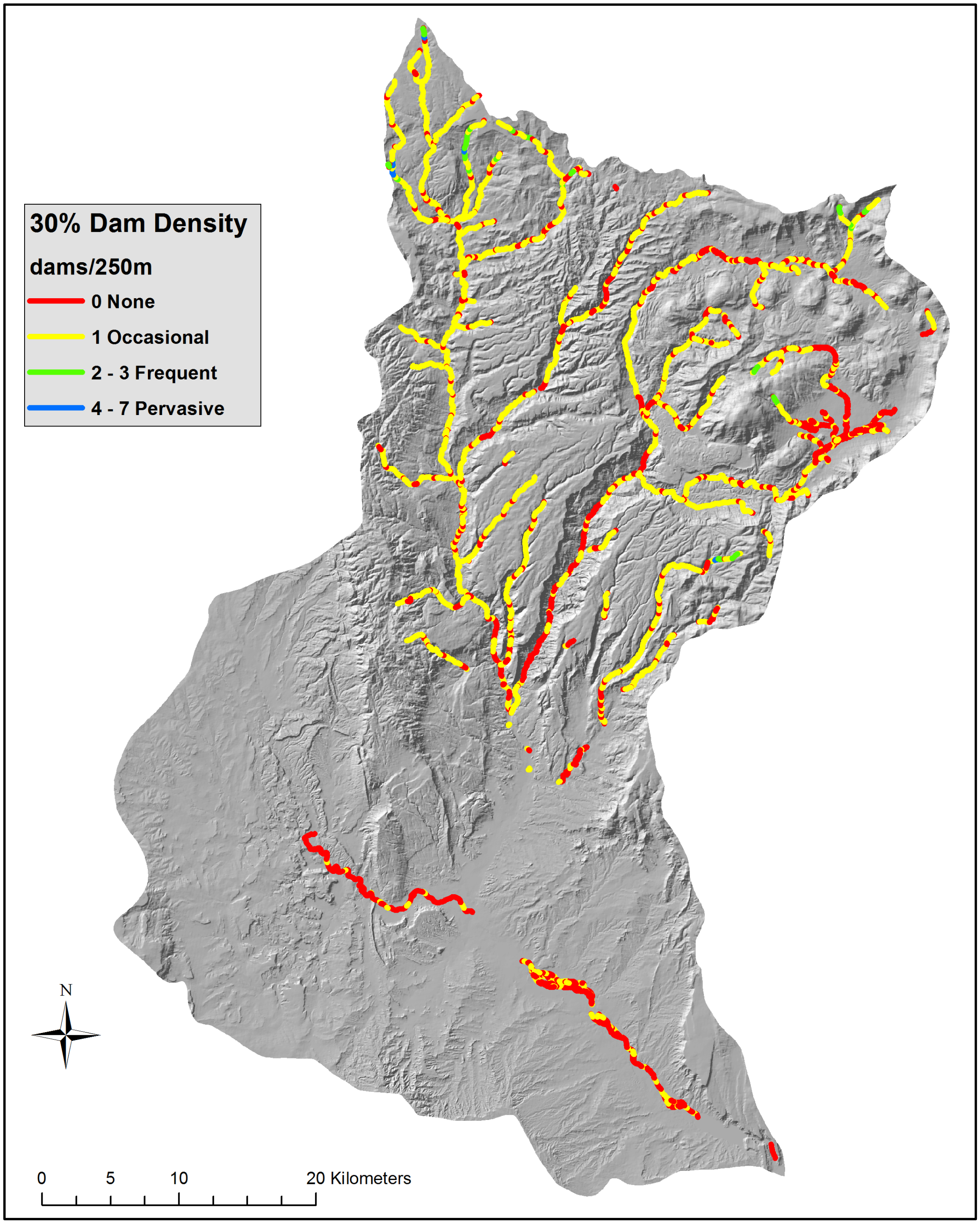

Figure 2.3 - G, BRAT Output Results at 30% Capacity in the Jemez Watershed

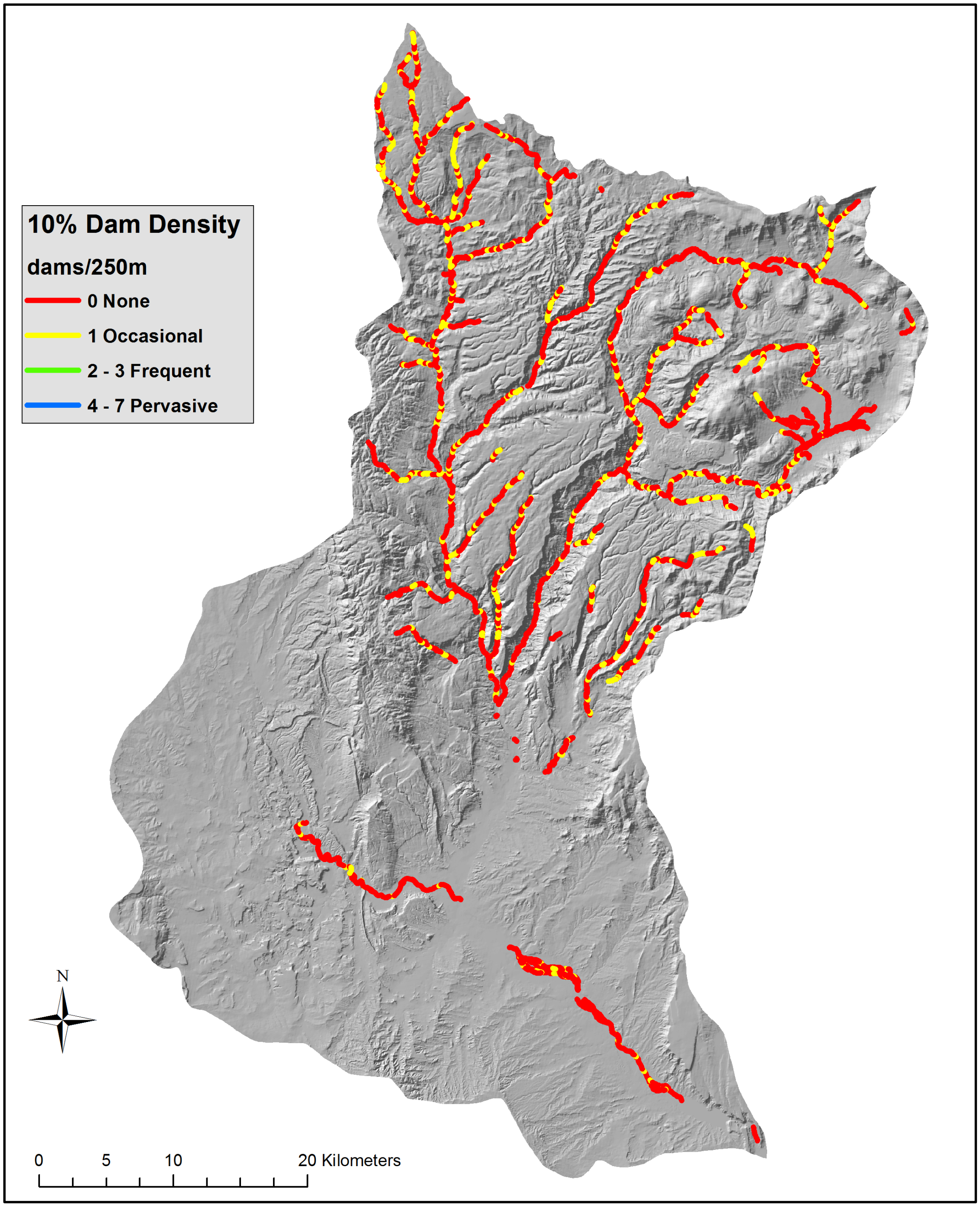

Figure 2.3 - H, BRAT Output Results at 10% Capacity in the Jemez Watershed

The output from the BRAT model is necessary for the subsequent objective of hydrologic modeling (Chapter 3) to determine the impacts of beaver dams on biodiversity provisioning services and hydrologic flows in the Jemez Watershed. In addition, the output of the BRAT model allowed estimation of the number of beaver colonies that one could expect in the Jemez Watershed and of flooded area and additional riparian habitat. This facilitated the framing of the ecosystem assessment for beaver re-establishment in the Jemez Watershed (Chapter 4).

Limitations

The application of the BRAT model to the Jemez Watershed has some limitations. The first limitation is the need to use parameters and rules developed in other watersheds. Although all parameters can be modified within the model, our team did not have the necessary resources to conduct extensive field trials for the current parameters in order to provide changes. Similarly, the outputs of the BRAT model for the Jemez Watershed remain unverified. When the model was developed on the Escalante River, the developers were able to validate the outputs, with good results. A recently published poster from New Mexico State University outlines the results of their statewide beaver dam survey (section 1.3.6) where only three active beaver dam sites were found in the Jemez Watershed (Figure 1.3-G), underlining the difficulty of validating the results.

Other limitations of the BRAT model as adapted to the Jemez Watershed are inherent to the data. Stream power for the region comes from generalized regression curves and does not necessarily capture the dynamic and flashy nature of the Jemez Watershed. In addition, inspection of the NHD stream layer (Figure 1.3-D) and aerial imagery of the region showed that the dataset captured regions as perennial that did not appear to be in the images. Conversely, the data did not capture reaches that appeared to be perennial. This is problematic because the model may have the tendency to over or under estimate the amount of reaches that beaver could inhabit, without being able to determine which direction the trend goes. In the northwest corner of the watershed (Figure 1.3-B), which is the target for modeling efforts, the NHD stream network and aerial observations seem to correlate adequately. Therefore, the predicted dam density in this region is likely accurate within the bounds of the model.

3.0 HYDROLOGIC MODELING

3.1 Introduction

Hydrologic models have a wide range of applications including water and sediment accounting, flood risk assessment, water supply analysis, and, in the case of our project, flow modification. Depending on the nature of the issue being explored, a number of approaches can be taken to guide a hydrologic investigation. For example, most flood risk assessments focus on modeling a watershed's runoff response to a single storm event, whereas water and sediment accounting focus on water and sediment sources, storage, and output for a given watershed.

This project uses hydrologic modeling to assess the impact of beaver re-establishment on the flow timing of the Jemez River. Several models were examined, and the US Army Corps of Engineers (ACOE) Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was determined to be the most suitable.

The HEC-HMS model was used to capture the Jemez Watershed's hydrologic characteristics through spatial analysis of soil, vegetation, land cover, and meteorological data. Then the model's calculated outflow was calibrated to observed outflows from the watershed. Finally, simulated beaver dams were inputted to the model to observe the impacts of beaver dams to the flow timing of the calculated outflow. These dams were inserted into the Rio de las Vacas sub-basin in the north-west corner of the watershed (Figure 1.3-D). The calculated hydrographs from the model without dams ('no dam' scenario) and from the model with dams ('dam' scenario) were then compared to determine the effect of beaver dams on stream flow.

3.2 Methods

3.2.1 Model Selection Process

To select the proper model for this objective, the following model characteristics were considered to be important:

- **Deterministic:** the model needed to parameterize hydrologic characteristics of the watershed and be capable of replicating past hydrographs
- **Continuous:** the model needed to account for water in the system during both storm events and periods of no precipitation
- **Distributed:** the model needed to account for spatial variability at a reasonable resolution

- **Baseflow:** the model needed to incorporate baseflow, including infiltration, storage, and interflow of water in the subsurface

- **Beaver Pond:** the model needed to be able to mimic a beaver dam and the associated reservoir

- **Output:** the model output needed to produce an annual hydrograph

Several models were considered, including: the Regional Hydro-Ecologic Simulation System (RHESSys; Tague & Band, 2004; Tague & Grant, 2009), the Water Evaluation and Planning System (WEAP; SEI, 2013), and HEC-HMS (HEC, 1995). Of these models, HEC-HMS met all of the criteria above, and in addition to its capabilities, the model has a complementary ArcGIS toolbox, HEC-GeoHMS, which is a spatial interface of the model for parameterizing watershed characteristics that are exported and used in HEC-HMS.

The Hydrologic Engineering Center gives the following description for its HEC-HMS software:

> "The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.
>
> The program is a generalized modeling system capable of representing many different watersheds. A model of the watershed is constructed by separating the hydrologic cycle into manageable pieces and constructing boundaries around the watershed of interest. Any mass or energy flux in the cycle can then be represented with a mathematical model. In most cases, several model choices are available for representing each flux. Each mathematical model included in the program is suitable in different environments and under different conditions. Making the correct choice requires knowledge of the watershed, the goals of the hydrologic study, and engineering judgment.
>
> The program features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. A graphical user interface allows the seamless movement between the different parts of the program. Program functionality and appearance are the same across all supported platforms" (HEC, 2014)."

3.2.2 HEC-GeoHMS

HEC-GeoHMS (version 10.1) is a complementary set of ArcGIS tools for the HEC-HMS model that allows the user to delineate a watershed and estimate hydrologic parameters using spatial data. Once the model files for HEC-HMS are built in HEC-GeoHMS, they are exported and a compatible project file is generated for seamless transfer to the HEC-HMS model. The HEC-HMS project file contains information on hydrologic and meteorological parameters, as well as spatial information for rain and precipitation gauges.

Basin Pre-Processing

The Jemez Watershed was delineated using tools in the HEC-GeoHMS module on a 30 m DEM obtained from the USGS that was in the North American Datum (NAD) 1983 Universal Transverse Mercator (UTM) Zone 13N projection. The DEM was reconditioned to exaggerate known river channels in order that they be recognized as such during the flow analysis stage. Similar to the 'burning in' method for stream identification in ArcGIS, the recondition method overlays a map of known river channels, obtained from NHD, and lowers the elevation of DEM cells that intersect with the stream layer. In contrast to the 'burning in' method, the recondition method gradually lowers the adjacent cells to simulate a river bed, so that artificial islands are not created within the river network (Figure 3.2-A). Once the DEM was reconditioned, the HEC-GeoHMS module was used to define flow accumulation, flow direction, stream definition, and the boundary of the catchment.

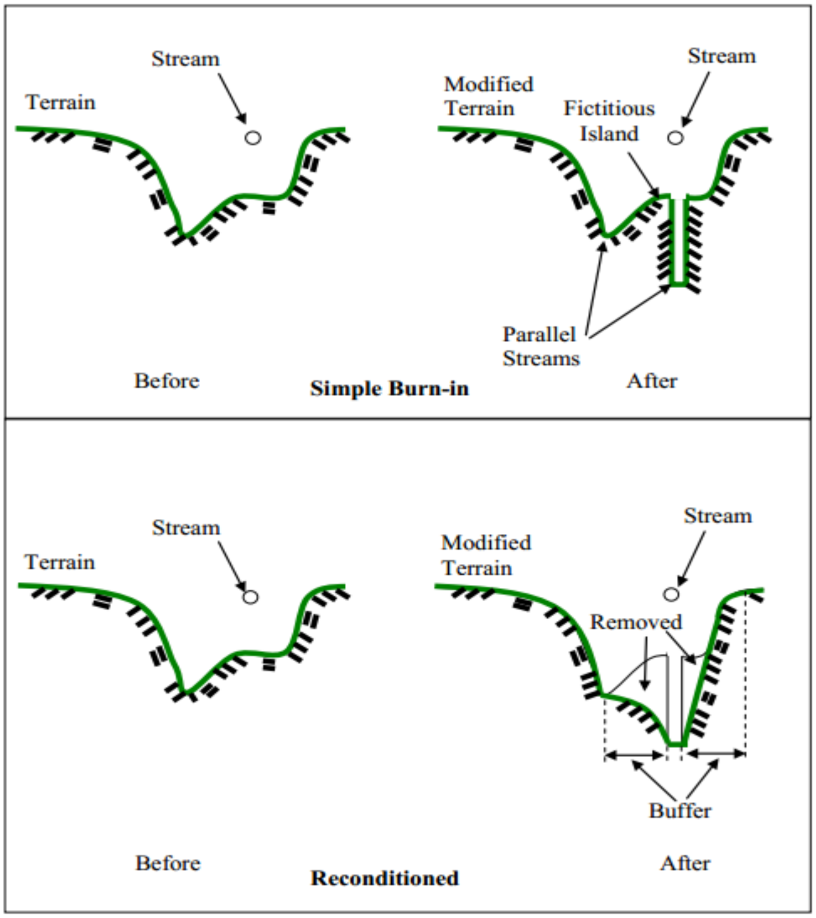

Figure 3.2 - A, Cross-Sectional View of the DEM River Channel Using the Reconditioned and Burn-in Methods

Source: HEC, 2010

After the catchment was delineated, an outlet point was set at the watershed drainage point, marking the outflow boundary for the system (Figure 3.2-B). Using this outlet, a project area was defined in HEC-GeoHMS, which the program recognizes as the boundary for estimating basin characteristics. Simultaneously, sub-basins were defined by the program based on a user-defined minimum area requirement of flow accumulation, set at 25 km^2, meaning that any stream segment, defined as a continuous reach that terminates at a river junction, must meet the minimum area requirements to be considered a separate sub-basin.

Setting the minimum sub-basin size was an important decision, as it determined the spatial resolution for sub-basin parameter estimation. If the threshold for minimum flow contributing area were too large, averaged sub-basin parameters would not accurately capture hydrologic characteristics of the watershed. Conversely, if the flow contributing area threshold were too small, the resolution would be finer than the available spatial data.

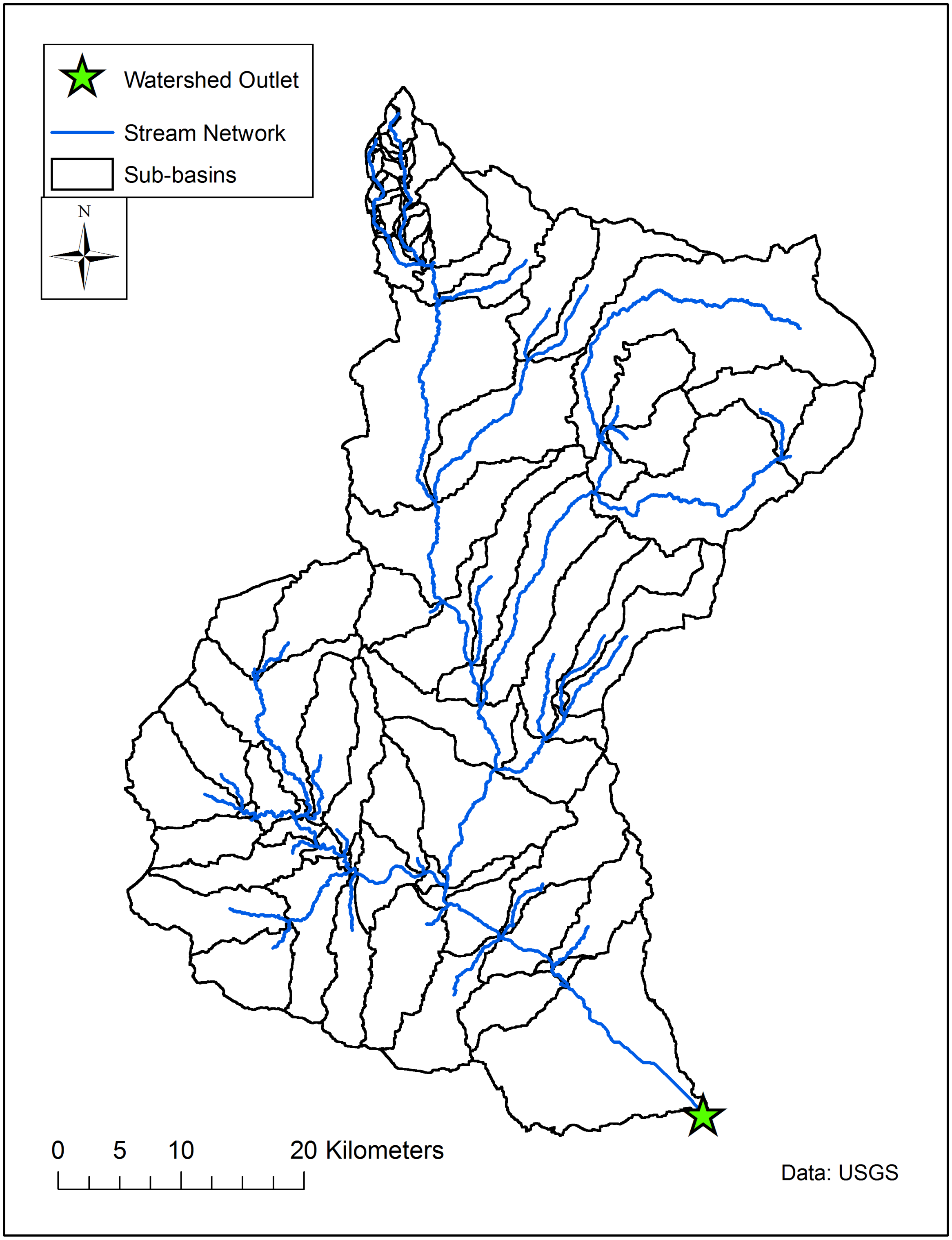

Figure 3.2 - B, Jemez Watershed with Stream Network and Sub-basins

Beaver Dam Placement

The placement of beaver dams in the watershed was determined using the BRAT output (section 2.3). Due to limitations of the BRAT model and the limitations of the HEC-HMS model it proved both inaccurate and impractical to model beaver re-establishment at 100% BRAT capacity over the entire watershed. The ecological factors combined with the intensive data HEC-HMS requires led to the decision to model beaver dams at 10% of BRAT capacity in the northwest corner of the watershed in the Rio de las Vacas study area (Figure 1.3-D). The location was chosen because BRAT predicted it to be a high beaver dam density area and the majority of the land is managed by the Santa Fe National Forest. The fact that the land is owned by one government agency, as opposed to many private users, makes the re-establishment of beaver more likely. The 10% BRAT output predicted the number of beaver dams per 250 m stream reach. The "create random points" ArcGIS tool was used to convert the predicted number to a point layer for the insertion of dams into the watershed. This tool randomly placed point features for the predicted number of dams along each 250 m BRAT stream reach, which amounted to the addition of 42 dams. This created the 10% beaver dam location GIS layer.

In order for the HEC-HMS model to recognize a beaver dam as part of the flow regime, it is necessary to create both an upstream and downstream link to the dam and corresponding reservoir. To accomplish this, each dam must have an upstream river reach and sub-basin associated with it, so that flow and storage can be computed as it moves through the dam. The goal of this project was to calibrate the model to a baseline observed flow and then compare the calibrated model stream flow to stream flow after the insertion of beaver dams. This process created a no-dam scenario and a dam scenario. To ensure the only difference between the models was the absence or presence of beaver dams, junction model elements were inserted into the model in the 'no dam' scenario as placeholders. After the 'no dam' scenario was calibrated these junctions were converted to reservoir model elements that were used to model the beaver dams.

To create the system of sub-basins to define the beaver dam locations first all sub-basins along the Rio de las Vacas were merged into one sub-basin. Then the 10% BRAT beaver dam location GIS layer was imported into HEC-GeoHMS. For each beaver dam a sub-basin was created manually using the "subdivide basin" tool included in the HEC-GeoHMS package. The result is that areas with simulated beaver dams were subdivided into small sub-basins as a result of their close proximity to one another (Figure 3.2-C).

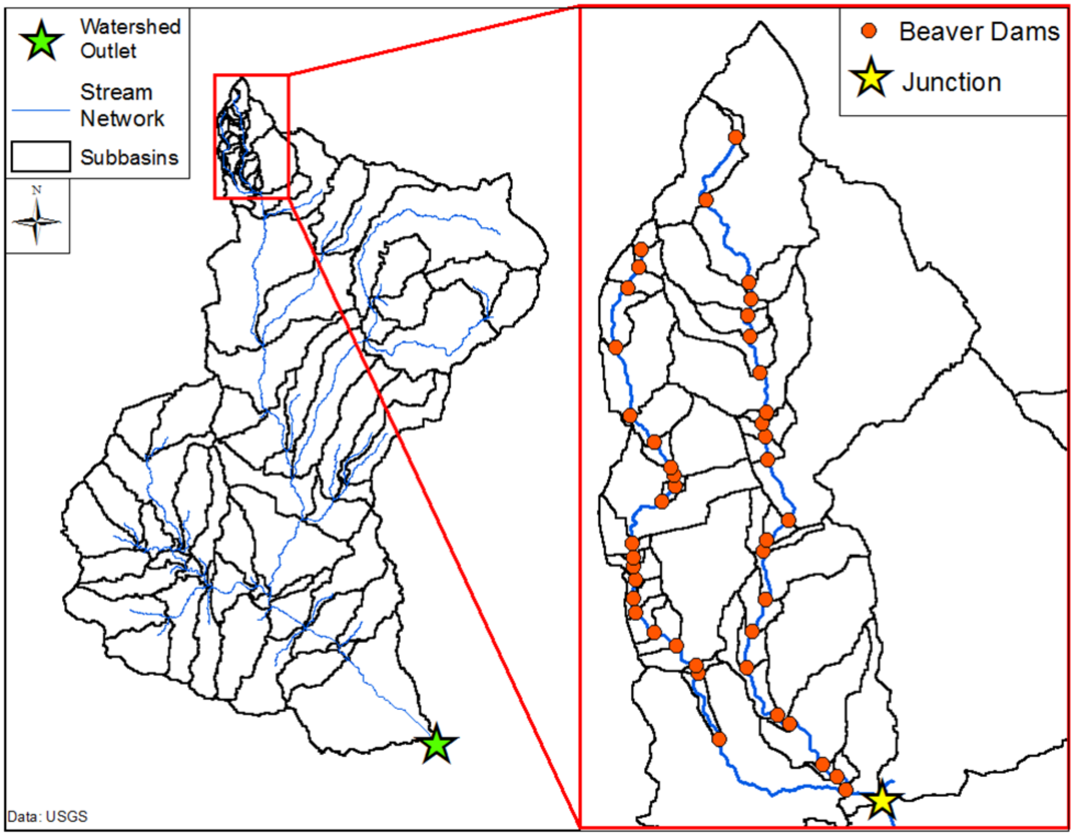

Figure 3.2 - C, Subdivided Beaver Dam Watershed

Model Precipitation Accounting Methods

The HEC-HMS model has different methods for accounting how water moves through a watershed. The user has the option of selecting from different loss, transform, baseflow, and routing methods. The loss method accounts for how precipitation is infiltrated to the soil and how it is accounted for. The transform method accounts for how precipitation, in excess of infiltration, is converted to surface runoff and how it reaches the river channel. The baseflow method accounts for how precipitation that has infiltrated to the subsurface moves as groundwater flow and interflow.

Loss Method: Soil Moisture Accounting. The Soil Moisture Accounting (SMA) loss method was selected because it is the only loss method that has the capability for continuous modeling on an annual basis. This method determines how much and how fast precipitation will be lost to five different storage components (Figure 3.2-D). Each storage compartment is assigned a total storage value, and the soil compartments include rates of influx and outflow. For example, once the total amount of precipitation stored in the canopy compartment exceeds the maximum, additional precipitation will be added to the surface storage compartment. After the surface storage compartment is filled, excess precipitation will infiltrate to the soil storage compartment at a fraction of the maximum soil infiltration capacity relative to soil saturation. Once the soil compartment storage is filled, precipitation will then percolate to the first groundwater storage compartment until it is filled, and excess percolation to the first groundwater storage compartment will percolate to the second groundwater storage compartment.

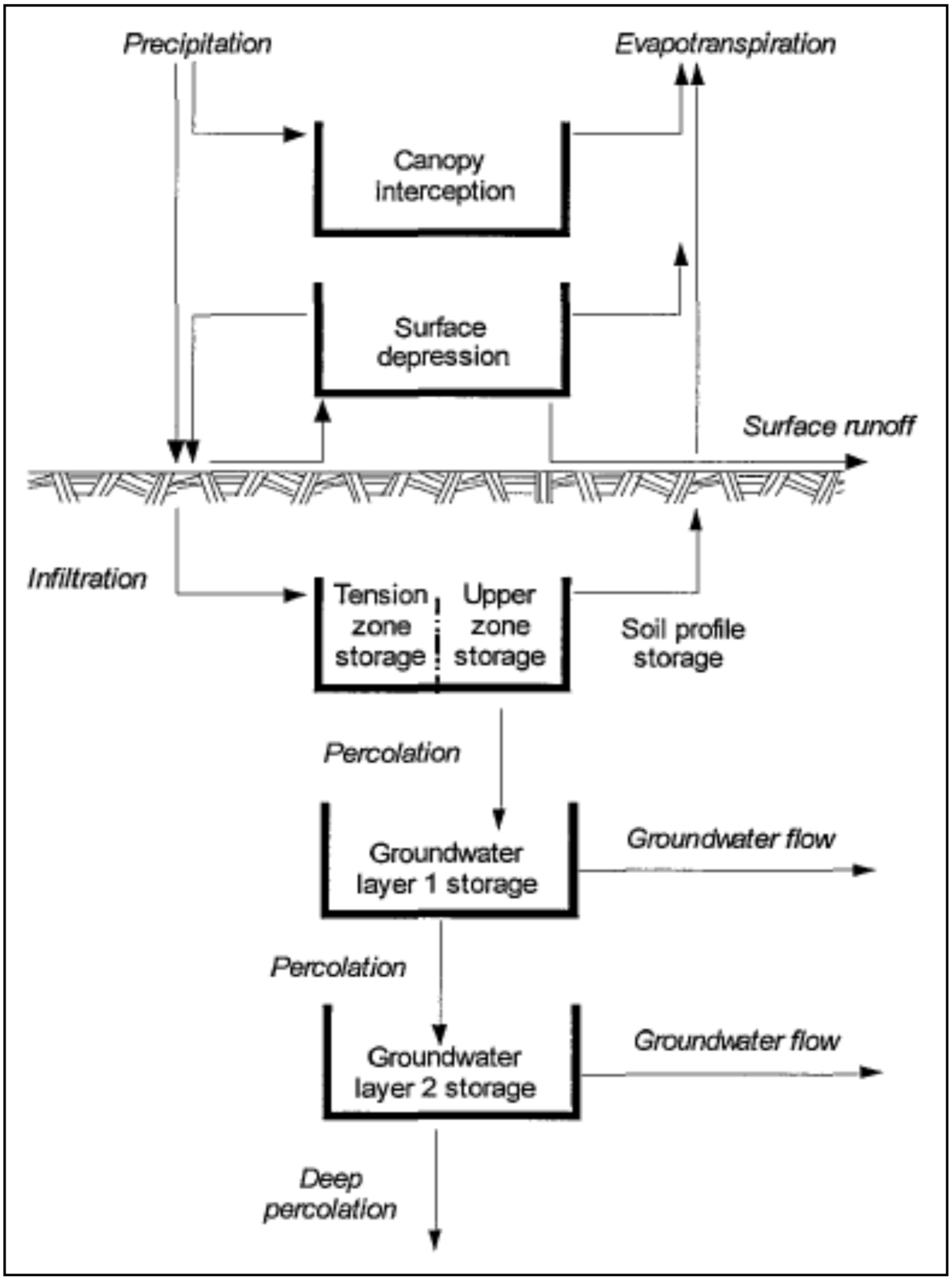

Figure 3.2 - D, Soil Moisture Accounting Loss Method Diagram

Source: HEC, 2010

Transform Method: Clark. The Clark transform method was selected because the HEC-HMS model has a built-in time-area curve algorithm for this method that is used to develop a 'translation hydrograph' that results from a burst of precipitation. The time-area curve establishes a relationship between the travel time and a percent of the sub-basin that may contribute runoff during that travel time. The time at which 100% of the upstream drainage area is accounted for at the outlet is said to be the time of concentration. Once the translation hydrograph has been created, the program then routes the hydrograph through a linear reservoir to account for storage attenuation effects across the sub-basin.

Other transform methods require the user to analyze historic hydrographs in order to determine the sub-basin lag time and storage attenuation. This was not possible, because in order to do this, each sub-basin would have to have its own dedicated stream gauge and corresponding precipitation data. Furthermore, the other transform methods were primarily developed for predicting storm runoff in predominantly urban and agricultural lands.

Baseflow Method: Linear Reservoir. The model requires that the Linear Reservoir baseflow method be used in conjunction with the SMA loss method in order to account for lateral flow between the 2 groundwater storage compartments. Inflow to the 2 groundwater storage compartments is controlled by the percolation rates of the compartment above, but the lateral flow output from these compartments is equal to the scaled soil infiltration rate. As with the transform method, the lateral flow hydrograph is routed through a reservoir to account for storage attenuation. Each sub-basin can be assigned one or more reservoirs, whereby increasing the number of reservoirs the storage attenuation is increased.

Routing Method. No river routing method was selected for the project for two reasons. First, the annual hydrograph was the desired output of the model, so the time step used for the boundary conditions was a 24-hour period. Therefore, the river routing method would be mostly nullified, as storage attenuation from river routing would be on the scale of hours. Second, the spatial data to compute average reach and river bank slope was not available at the resolution required for an accurate estimation.

Spatial Datasets

The primary function of the HEC-GeoHMS module is to use GIS datasets as a means for estimating generic sub-basin properties (area, average slope, flow accumulation, etc.) and parameters associated with each of the hydrologic methods described above, and to create a spatially weighted meteorological map of time-series precipitation based on gauge location. This section describes the various parameters and associated datasets used to estimate values for each.

State Soil Geographic (STATSGO) Database. The USGS STATSGO database contains information regarding soil properties at spatial resolution roughly equivalent to that of the sub-basins. The National Resource Conservation Service (NRCS) recommends that use of the dataset provide the following statement: "STATSGO is designed to support regional, multistate, State, and river basin resource planning, management and monitoring" (USDA, 2010).

The STATSGO soil characteristic values were converted to a raster dataset, the ArcGIS field calculator was used to assign values to each cell, then the 'Sub-basin Parameters from Raster' tool in the HEC-GeoHMS module was used to estimate average sub-basin values for the soil parameters of the SMA loss and Linear Reservoir baseflow methods.

STATSGO soil values used in the analysis included the following:

- **Available Water Capacity (AWC):** value of available water capacity for the soil layer or horizon, expressed as inches/inch

- **Soil Permeability (SP):** value for the permeability rate for the soil layer or horizon, expressed as inches/hour

- **Soil Thickness (ST):** value of the depth of the soil layer or horizon, expressed in inches

- **Liquid Limit (LL):** value for the liquid limit of the soil layer or horizon, expressed as percent moisture by weight

- **Soil Bulk Density (SBD):** value of moist bulk density of the soil layer or horizon, expressed as grams per cubic centimeter

National Land Cover Database. The National Land Cover Database (NLCD) percent developed impervious surface provides nationally consistent estimates of the amount of man-made impervious surfaces present over a given area in a seamless form. These raster data sets are derived from Landsat satellite imagery, using classification and regression tree analysis. Values range from 0 to 100 percent, indicating the degree to which the area is covered by impervious features. While the NLCD raster dataset contains values for percent impervious surface that result from human development, large impervious rock outcrops, which are also considered impervious, are reflected by data from the STATSGO database in that they have a soil permeability value of 0.

LANDFIRE Reference Database. LANDFIRE is a partnership sponsored by the Wildland Fire Leadership Council with the US Department of the Interior, the US Department of Agriculture-Forest Service, and The Nature Conservancy. The data used was the "Existing Vegetation Type" raster with a cell size of 30 m by 30 m. This dataset contains the existing vegetation type for each 30 m cell in the watershed, and was used to calculate canopy interception values for the model.

Through consultation with Aubrey Dugger (personal communication, November 2013), who is conducting research in a nearby watershed, plant interception capacities for local plants were obtained. Due to the small amount of interception, rough estimates were deemed appropriate for these values. Therefore, the LANDFIRE data were generalized into the 8 vegetation types (Table 3.2-A) with available interception capacities. The LANDFIRE dataset was then reclassified from vegetation types to interception capacities.

Table 3.2 - A, Generalized LANDFIRE Vegetation Types and Interception Capacity

Vegetation Type	Interception Capacity (mm)
Ponderosa Pine	1
Spruce-Fir	4
Douglas Fir (Mixed Conifer)	3
Gambel Oak	1
Alpine grass	0.2
Riparian (Willow, Cottonwood)	1.5
Pinon-Juniper	1
Shrub	1

Source: LANDFIRE, 2013; Aubrey Dugger (personal communication, November 2013)

Western Regional Climate Center Precipitation Database. The Western Regional Climate Center (WRCC) is part of the larger Regional Climate Center (RCC) program hosted by the National Oceanic and Atmospheric Administration (NOAA). These RCCs provide climate services for local, state, and federal governments. The WRCC acts as a repository of historical climate data. Precipitation data for the Jemez Watershed could be found using historical data from 13 rain gauge sites (Figure 1.3-C). The data available at each of these gauges were recorded on a daily basis for varying lengths of time.

Calculation of HEC-HMS Parameters Using Spatial Datasets

Using the datasets described above, spatial raster datasets were created with the ArcGIS field calculator. Then, the 'Sub-basin Parameter from Raster' tool from the HEC-

GeoHMS module was then applied using these raster datasets as inputs to estimate hydrologic parameters for the different HEC-HMS methods, which included:

- **Maximum Soil Infiltration (MSI) Raster:** the maximum rate at which precipitation in excess of maximum storage for the surface storage compartment will enter the soil storage compartment used in the SMA loss method
    - Calculation: MSI = SP

- **Maximum Soil Storage (MSS) Raster:** the maximum amount of precipitation that can be stored in the uppermost soil layer used in the SMA loss method
    - Calculation: MSS = ST x SBD X LL / density of water

- **Maximum Soil Tension Storage (MSTS) Raster:** the amount of precipitation in soil storage that is held against gravity; all precipitation stored in the soil above this threshold is available for percolation to the groundwater storage compartment used in the SMA loss method
    - Calculation: MSTS = MSS – AWC

- **Maximum Soil Percolation (MSP) Raster:** the maximum rate at which precipitation stored in MSS, in excess of MSTS, will enter the first groundwater storage compartment (GW1) used in the SMA loss method
    - Calculation: MSP = SP x 0.2

- **Maximum Groundwater Storage (MGS) Raster:** the maximum amount of precipitation that can be stored in the upper groundwater storage (MGS1) and lower groundwater storage (MGS2) used in the SMA loss method
    - Calculation: MGS1 = MSS x 3 & MGS2 = MSS x 5

- **Maximum Groundwater Percolation (MGP) Raster:** the maximum rate at which precipitation will leave the upper groundwater storage and enter the lower groundwater storage (MGP1) and leave the lower groundwater storage to deep groundwater storage (MGP2) used in the SMA loss method
    - Calculation: MGP1 = MSI x 0.1 & MGP2 = MSI x 0.5

- **Percent Impervious Surface (PIS) Raster:** the percentage of impervious surface due to human development used in the SMA loss method
    - Percent developed impervious raster dataset from the NLCD

- **Maximum Canopy Storage (MCS) Raster:** the volume of water per unit area of water intercepted by vegetation used in the SMA loss method
    - The LANDFIRE dominant life form raster dataset determined the existing vegetation cover and volume per unit area storage values were assigned to dominant plant species based on the values in Table 3.2-A

- **2-year 24-hour Rainfall Raster:** the daily precipitation associated with a 2-year flood used to estimate the time of concentration for the Clark transform method
    - Calculation: historical precipitation data from the WRCC was analyzed to determine the precipitation volume at each gauge for a 2-year flood event, which were used to create the 2-year 24-hour Rainfall Raster

- **Total Storm Precipitation Raster:** the daily precipitation associated with large storm events used to estimate the Time of Concentration (TC) for the Clark transform method
    - Calculation: historical precipitation data from the WRCC database was analyzed to determine the daily precipitation volume for each rain gauge that simulate a "large storm event", which were used as a total storm volume for each gauge

- **Time of Concentration (TC):** the maximum travel time in a sub-basin, used in the development of the translation hydrograph for the Clark transform method
    - Calculation: the HEC-GeoHMS module has a built-in algorithm for the NRCS TR-55 method for calculating the TC for each sub-basin, which uses 2-year 24-hour rainfall amount, slopes, and flow distance of precipitation excess to streams to estimate the TC for each sub-basin

- **Storage Coefficient (SC):** a value that accounts for storage effects of the linear reservoir through which the translation hydrograph is routed for the Clark transform method
    - Calculation: many field studies have found that SC / (SC + TC) is reasonably constant over a region; therefore, an iterative process to optimize the lowest standard deviation of the above equation was used to obtain a reasonable SC value

Creation of .HMS File for Import to HEC-HMS

The final step of the HEC-GeoHMS module is to create an .HMS project file which is the operational file for the HEC-HMS model. The .HMS file pulls information from three files: the .basin file, .met file, and .gage file. In addition to these files, the .HMS project file asks the user to specify Control Specifications, which defines the HEC-HMS project simulation duration and time step. By defining the .basin file, .met file, .gage file and control specifications, an .HMS file can be exported using the HEC-GeoHMS module. This process is the culmination of the HEC-GeoHMS module and it serves the purpose of creating a spatially distributed model that the HEC-HMS program can use.

Creation of .basin File for Import to HEC-HMS

The HEC-GeoHMS module has a series of functions that prepares the hydrologic parameters and other data associated with each HEC-HMS element (discussed in section

3.2.3) for export to the HEC-HMS program. The result of these functions is to create the .basin file, which contains parameter values for each of the HEC-HMS elements. First, the module maps the connectivity between sub-basins, river reaches, junctions, reservoirs, diversions, sources, sinks, and outlets. Next, spatial coordinates are added to each of these elements. Finally, estimated hydrologic parameter values are translated from an ArcGIS table to the .basin file.

Creation of .met and .gage File for Import to HEC-HMS

The meteorological model is created in HEC-GeoHMS and is used in HEC-HMS to simulate the precipitation patterns for the hydrologic model. The HEC-GeoHMS module has four options for creating a meteorological model which results in both a .met file as well as a .gage file. The .met file is the meteorological model which is used in HEC-HMS while the .gage file contains a list of precipitation gauges that will be used by the meteorological model.

To create the meteorological file, the gauge weight method was used in HEC-GeoHMS. It was determined that using this method in creating such a file would be the most effective due to the wide range of environmental conditions that could be found within the watershed. The northern half of the watershed can be characterized as montane forest while the southern half is arid drylands. Precipitation gauges located within the northern section of the watershed would not accurately reflect the meteorological conditions that exist for the southern section. In order to address this potential discrepancy, precipitation gauges that were outside of the watershed were also used to create the meteorological file. These gauges would better reflect the arid conditions in the lower basin. The gauge weight method would then distribute the precipitation volumes spatially across the watershed. Using ArcGIS, a precipitation gauge layer was used to establish spatial coordinates of each gauge. Then, Thiessen polygons were created, establishing areas of influence for each rain gauge. Any location within the polygon would be closer to its corresponding rain gauge than to any other gauge. This allowed precipitation values to be appropriately distributed spatially throughout the basin (Figure 3.2-E).

Figure 3.2 - E, Jemez Watershed Thiessen Polygons

3.2.3 HEC-HMS

Hydrologic elements are the basic building blocks of a basin model. An element represents a physical process such as a watershed catchment, stream reach, or confluence. Each element represents part of the total response of the watershed to atmospheric forcing. Seven different element types are included in the program: sub-basin, reach, reservoir, junction, diversion, source, and sink.

An element uses a mathematical model to describe the physical watershed and precipitation accounting. The model is only an approximation of the physical process over a limited range of environmental conditions. Data availability and the required parameters of a model can also determine fitness. There are 11 different loss methods, 7 transform methods, and 5 baseflow methods that can be selected for each sub-basin (HEC, 2010).

The HEC-HMS model uses precipitation and evapotranspiration (ET) as boundary conditions, meaning that mass is conserved in that there cannot be any water in the system in excess of the difference between precipitation and ET (with the exception of diversions and user defined sources). Precipitation is added to the system through time-series data from precipitation gauges and it can only leave the system through ET or discharge at an outlet. Otherwise, precipitation is stored in sub-basins, river reaches, or reservoirs.

As reported in section 3.2.2, the SMA loss method, the Clark transform method, and the Linear Reservoir baseflow method were selected, which dictate how the program will calculate the partitioning and transferring of water between sub-basin and reach elements. For the sake of the paper, we will collectively call these methods HEC-HMS accounting methods. The HEC-HMS model uses the accounting methods as the basis for precipitation accounting, where water can be stored in a sub-basin, a river, a reservoir, or as runoff. Each of the HEC-HMS accounting methods has parameters associated with them that tell the program how much and how long precipitation will be stored in the associated compartments.

Precipitation that is stored in a canopy, surface, soil, river, or reservoir compartment is subject to ET. ET rates are a function of temperature, elevation, and water surface area.

HEC-HMS Model Elements

There are 7 different HEC-HMS model elements: sub-basin, reach, reservoir, junction, diversion, source, and sink. Only sub-basin, reach, junction, reservoir, and sink elements were used in this project.

- **Sub-basin elements** represent the physical watershed and are linked to both upstream and downstream sub-basin elements through both surface and subsurface flow. Surface inflow to sub-basin elements can come from any of the other 6 model elements as well, but subsurface inflow can only come from another sub-basin element or reach element (only if loss/gain reach method is selected).

  - The SMA loss method accounts for precipitation that falls within a sub-basin element that is in excess of ET and not converted to runoff (precipitation stored in the surface storage compartment that is in excess of the infiltration rate to the soil storage compartment).
  - The Clark transform method accounts for runoff in a sub-basin element, which is precipitation in excess of ET and soil infiltration.
  - The Linear Reservoir baseflow method accounts for subsurface flow between adjacent sub-basin and reach elements that is within either of the groundwater storage compartments of the SMA loss method.

- **Reach elements** convey stream flow through the simulated watershed and can receive inflow from any number of model elements. Surface inflow to a reach element can come from adjacent reach, sub-basin (runoff), junction, source or reservoir elements, but subsurface inflow can only come from sub-basin elements with the loss/gain method selected. Outflow from a reach element is calculated as the inflow with a routing and/or loss method applied to account for translation and attenuation.

- **Junction elements** are used to combine stream flow from adjacent upstream sub-basin, reach, reservoir or source elements. The outflow from a junction element is simply the sum of all inflows to the junction.
  - Junction elements were used as placeholders for reservoir elements in the 'no dam' scenario

- **Reservoir elements** are used to model the detention and attenuation of hydrograph caused by a reservoir or detention pond. Inflow to a reservoir element can come from any number of upstream sub-basin, reach, source, or reservoir elements. Outflow from reservoir elements can be calculated using one of three routing methods.
  - Reservoir elements were used to model beaver dams

- **Sink elements** are used to represent the outlet of the physical watershed. Surface inflows to a sink element can come from any number of upstream reach, sub-basin, source or reservoir elements, but only sub-basin elements with a baseflow method can contribute a sink element inflow. There is no outflow from a sink element.
  - A sink element was placed at the outlet of the physical watershed at the location of the USGS Jemez Dam stream gauge (Figure 3.2-B)

Preparing HEC-HMS Model

The majority of the hydrologic and meteorological parameters were estimated in the HEC-GeoHMS module and exported to an .HMS and associated .basin, .met, and .gage files. In addition to these parameters, several initial conditions, temperature elevation bands, a melt rate function, and time-series data for temperature, precipitation and stream discharge needed to be defined and linked to appropriate model elements before the model was functional.

Basin Model. In addition to the parameters estimated using HEC-GeoHMS for the basin model, an initial moisture content had to be defined for all SMA loss method storage compartments, as well as initial discharges and lag coefficients for both groundwater storage compartments of the Linear Reservoir baseflow method for each sub-basin element.

Since simulations started at the beginning of each water year (October 1st), historic September precipitation levels and flow characteristics of the watershed were analyzed. Using this information, the initial moisture content of each SMA loss method storage compartment was estimated and initial discharge and lag coefficients of groundwater storage compartments of the Linear Reservoir baseflow method. These values were refined during the calibration process.

Meteorological Model and Time-Series Data. In order for the meteorological model to properly function in HEC-HMS, precipitation data needed to be linked to hydrologic elements. The precipitation gauges would have been inputted into the model by selecting the appropriate .met file, which included a .gage file containing the list of precipitation gauges used in the model. Parameter data describing the gauges used is specific to each sub-basin. Using the *Component Editor*, each sub-basin can be assigned precipitation gauges, each with its own weight of influence upon the sub-basin.

Data that are recorded on a regular basis are important for estimating basin-average rainfall. A time-series of flow data, referred to as observed flow is required for calibrating the model. Such data can be stored as a gauge and can provide information on discharge, precipitation, and temperature.

The precipitation and temperature data were obtained from the WRCC climate stations run by the VCNP. The discharge gauge data were obtained from the USGS. HEC-DSSVue was used to create .dss (data storage system) files to enter the data into HEC-HMS. Dss is the database system used to store sequential input data into HEC-HMS. .dss files were created for the 12 temperature and precipitation gauge stations and the 1 stream discharge station in the watershed. Table 3.2-B provides gauge names, types, and duration of data from the rain gauges (Figure 1.3-C). The upper basin had excellent rain and temperature gauge data, but the lower basin only had 1 station. Three (3) precipitation and temperature stations had significant data gaps associated with them.

Where there was only 1 day missing, the average of the day before and after the missing date were found and entered. The Jemez station had information from the nearby Wolf Canyon station entered to replace larger gaps. The Coyote station had large missing ranges replaced with data from the nearby Vacas Locas station. The Jemez Dam had missing data replaced with data from the nearby Placitas station, which is not included as a station in the analysis but is nevertheless located near the station.

Table 3.2 - B, Jemez Time Series Gauges

Gauge Name	Elevation (m)	Data Type	Date Range
Jemez Springs	1924	Precipitation and Temperature	2010 - 2013
Conejos	2490	Precipitation and Temperature	2011-2013
Cebollita Spring	2496	Precipitation and Temperature	2011-2013
San Antonio	2598	Precipitation and Temperature	2004 - 2013
Valles Caldera National Preserve Headquarters	2644	Precipitation and Temperature	2003 - 2013
Coyote	2682	Precipitation and Temperature	1996 - 2013
Los Posos	2738	Precipitation and Temperature	2004 - 2013
Valle Toledo	2750	Precipitation and Temperature	2005 - 2013
Redondo Peak	3067	Precipitation and Temperature	2004 - 2014
Wolf Canyon	2505	Precipitation and Temperature	2011 - 2013
Jemez Dam	1642	Precipitation and Temperature	2002 - 2013
Jemez River	1713	Discharge	1936 - 2013

The Temperature Index method within HEC-HMS was selected to model snowmelt in the Jemez Watershed. The method is based on assigning a specified amount of melt for each degree above freezing, taking into account atmospheric and snowpack conditions.

Relevant components of the model include the precipitation temperature, or PX temperature, which controls what type of precipitation falls in the watershed. If modeled temperatures are above 1.1 °C, the precipitation is assumed to fall as rain. Conversely, if it is below, the precipitation will fall as snow. Base Temperature, which in simple terms controls the temperature at which the snowpack begins to melt, was set at freezing, or

0°C. Wet meltrate, an index of the amount of melt occurring in the snowpack when precipitation is falling as rain was set at 4.2mm/ºC-Day. All other components were set at common values as estimated from the HEC-HMS User Manual or through personal communication with HEC technical support staff (Table 3.2-C).

Table 3.2 - C, Temperature Index Method Value

Temperature Index	Value
PX Temperature (°C)	1.1
Base Temperature (°C)	0
Wet Meltrate (mm/°C-day)	4.2
Rain Rate Limit (mm/day)	10.6
ATI-Meltrate Coefficient	0.98
Cold Limit (mm/day)	20.3
ATI Coldrate Coefficient	0.84
Water Capacity	5
Groundmelt (mm/day)	0

In addition, an Antecedent Temperature Index (ATI)-Meltrate Function was constructed from published studies using HEC-HMS in snowy regions and the HEC technical support staff (Duishonakunov, 2008). The ATI-Melrate function specifies, in conjunction with the above parameters, how much snow melts out of the snowpack for each degree that is occurring above freezing for each day of the simulation.

After setting the generalized parameters for the snowmelt model, each sub-basin must be customized individually. Specifically, a temperature station must be linked, a lapse rate defined, and elevation bands created.

To define the atmospheric temperature at any given time step for each sub-basin, the closest available temperature station was linked to the sub-basin of interest. Temperatures did not vary spatially within each sub-basin. Then, a standard atmospheric lapse of (-6.49 °C / 1,000 m) was defined for all sub-basins. Finally, elevation bands were generated for each sub-basin. The goal of this process was to combine the measured temperature and the specified lapse rate to account for elevation change in the sub-basin and its effect on snowfall. Average elevation and elevation range for the sub-basins were calculated using the Zonal Statistics tool in ArcGIS. If the elevation range for a sub-basin was 300 m or less, one elevation band was constructed at the average elevation for that sub-basin. If the range was greater than 300 m, the sub-basin was divided into 300 m bands, with the first band's elevation at the minimum elevation for the sub-basin, then incremented 300 m upwards. All initial conditions for the elevation bands were set to 0 to reflect the group's assumption that no snow was present on the ground at the onset of the water year.

To incorporate ET into the model, the Monthly Average method, which uses pan evaporation data, was used. This was chosen to best reflect the capabilities and availability of data, as well as the best fit for long-term modeling required by the SMA loss method. Pan evaporation data was obtained from the WRCC and utilized values from the Jemez Dam station (Table 3.2-D).

Table 3.2 - D, Pan Evaporation Values

Month	Pan Evaporation (mm)
January	0.00
February	0.00
March	0.00
April	251
May	311
June	354
July	362
August	290
September	248
October	170
November	92
December	0.00

The monthly average method requires pan coefficients to more accurately estimate ET in the system. Pan coefficients attempt to normalize measured pan evaporation and correct for extra evaporation due to heating of the above ground portions of the measurement pan. By multiplying measured values by the coefficient, the model can better portray actual plant water use. A typical value for the correction coefficient is 0.7, which was used for the upper, more vegetated sub-basins in the Jemez Watershed. However, the lower reaches and sub-basins in the region are more characteristic of arid regions and less heavily vegetated. For these sub-basins, a smaller coefficient, 0.5, was used to reflect the lower plant water use. Finally, measured values of zero were set to be small positive values instead (0.01) to reflect the assumption at evaporation and thus ET continued in the lower reaches of the Jemez Watershed throughout winter at lower rates.

Setting Control Specifications. The control specifications set the time frame and time step over which the model runs. The time step determines the smallest unit of time for which the model runs through the calculations described above. HEC-HMS has the ability to run time steps as short as one minute and as long as one day. The model was run at the 1-day time step. The available precipitation data, temperature data, and stream flow data were available with 1-day time steps. The time frame chosen was water year 2012 (October 1, 2011-September 30, 2012). This was the first year that all 12 rain gauge stations had data and thus this year gave the highest resolution of precipitation data. The 2012 water year was also a dry year, viewing beaver dams effects on stream flow during dry years was of interest to observe if dams could extend flow in dry conditions.

Running and Calibrating the HEC-HMS Model

With all of the hydrologic and meteorological parameters, initial conditions, and time-series data defined and linked properly, the model was ready to run. A .basin file, .met file, .gage file, and control specifications were selected in the compute module and the model was run.

The computed hydrograph and observed hydrograph were overlaid and analyzed. Initially, the match was not good, so calibration was necessary. The HEC-HMS model contains an optimization algorithm for model parameters, but through coordination with ACOE HEC-HMS technical staff (M. Fleming, personal communication, 2014), it was determined that the algorithm does not work for models using the SMA loss method. Therefore, the model values needed to be refined through an iterative process.

The main issue with the calculated hydrograph was that baseflow would disappear during the winter months of each simulation. We adjusted the groundwater lag coefficients in order to prolong flow later into the season, but an analysis of the time series snow-water equivalent for each sub-basin indicated an issue with the snowmelt function. During the winter, precipitation was falling as snow when it should have been falling as rain, which was followed by an instantaneous melting of the entire snowpack in spring. The melt rate function was adjusted accordingly (M. Fleming, personal communication, 2014).

However, since the goal of the project was to observe the impact of beaver reintroduction on the flow and timing of summer baseflows, we decided the model was sufficiently calibrated for our purposes, given that the model accurately captured the frequency and magnitude of summer baseflow and storm runoff events over a 2-year simulation (section 3.3.2).

Inputting Beaver Dams

Once the model was calibrated, junctions in the Rio de las Vacas study area (Figure 3.2-C) were converted to reservoir elements. As discussed above, the junctions acted to combine inflow from upstream sources running through sub-basins. Reservoir elements instead simulate ponds with inflows from upstream and a downstream outflow. Each junction element was deleted, replaced with a reservoir element, and linked to downstream river elements and upstream river and sub-basin elements.

The "Outflow Structures" reservoir method was used to simulate beaver dams in the model. This method allowed dams to be placed in the river. The method allows the addition of many different structures in the stream channel and the calculation of parameters associated with these structures. Beaver dam characteristics can vary in height, porosity, method of drainage, and storage volume, changing based on the local geography of the stream and the age of the dam (Ming-Ko & Waddington, 1990). For ease of modeling every beaver dam in the stream flow model was given the same characteristics.

One dam top structure was then added at each reservoir element. The dam top structure is how HEC-HMS models a dam over which water can flow in an uncontrolled manner. Spillways can be added to allow water to flow over the dam in a controlled manner. This method allowed dam height, length, and a dam top coefficient to be set. The dam top height was set to 1 m to simulate the average height of a beaver dam (Beedle, 1991; Gurnell, 1998). The length of the dam was set to 3 m based on observations made in the field. The dam top coefficient, which accounts for the loss of energy as water approaches the dam, was set to 4 as the HEC-HMS manual gave a general range for dam top coefficient values between 2 and 4. A coefficient of 4 was chosen because the rough construction of beaver dam with logs and mud would create more drag and increase energy loss in the water.

HEC-HMS has two methods for calculating the volume of water stored in ponds: an elevation-area curve and an elevation-storage curve. HEC-HMS refers to the height of water in the pond as the pond elevation. The elevation-storage curve relates the elevation of water in the pond to a volume of water. The elevation-area curve is similar except the elevation of water is related to the surface area of the pond. The model then calculates storage volume using the conic formula. The elevation-area method was used as it allowed evaporation to be calculated from the surface of the pond. While evaporation was an important consideration, the volume of water stored in the pond was the most important. The model was run using American units so from this point forward model output and graphs are shown in American units. Beaver dams were determined to be able to impound ⅛ (0.125) of an acre-foot of water (Pollock et al., 2003). The curve was calculated linearly with an elevation of 0 ft equaling 0 acres of pond surface area. The surface area at an elevation of 3.3 ft was then iteratively varied. The model was run and the maximum storage in the beaver dam was observed. After several trials, a surface area of 0.08 acre-feet resulted in a maximum pond storage volume of 0.125 acre-feet. The curve was extended above 3.3 ft due to the need for the model to calculate overflow volume when the elevation of water was higher than the dam (Figure 3.2-F).

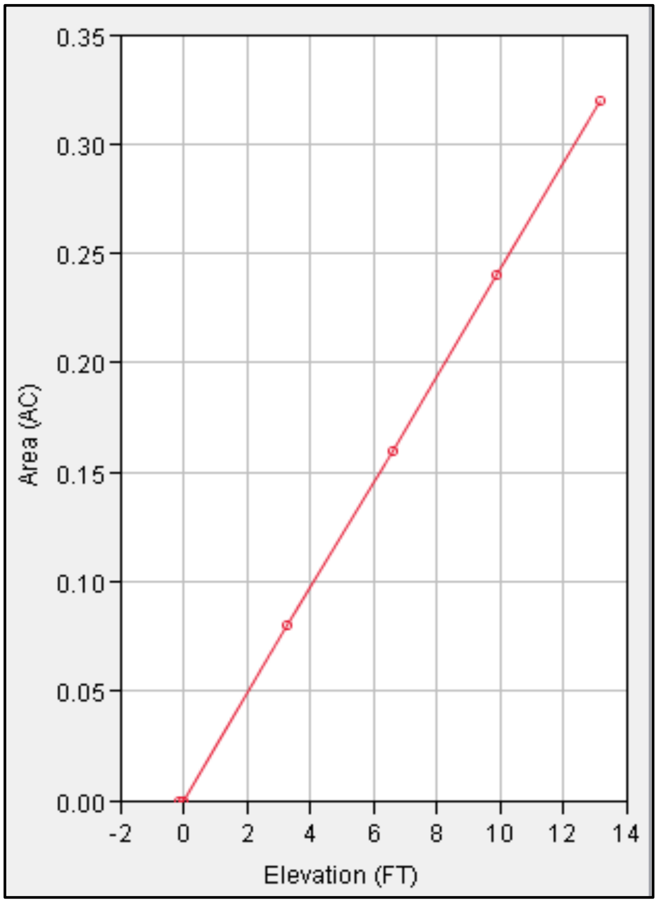

Figure 3.2 - F, Beaver Dam Elevation-Area Curve

The outflow structures method allowed for dam seepage to be taken into account. This is water that flows through the dam structure and can be an important loss of water from the pond. The model calculates seepage based on an elevation-discharge curve, which must be defined by the user. Devito and Dillon (1993) defined maximum outflow values of 5.3 cubic feet per second (cfs) with an elevation outflow curve but the water elevation only reached about half of the modeled dam height. Ming-Ko and Waddington (1990) found that active dams are “mostly impervious” and listed overflow as the main method of water escape. As the dams decayed however the dam would become more porous until it had little effect on the flow rate. Therefore, 5.3 cfs was set as the maximum seepage rate at a dam height of 3.3 ft, which fell linearly to a discharge of 0 at an elevation of 0 (Figure 3.2-G).

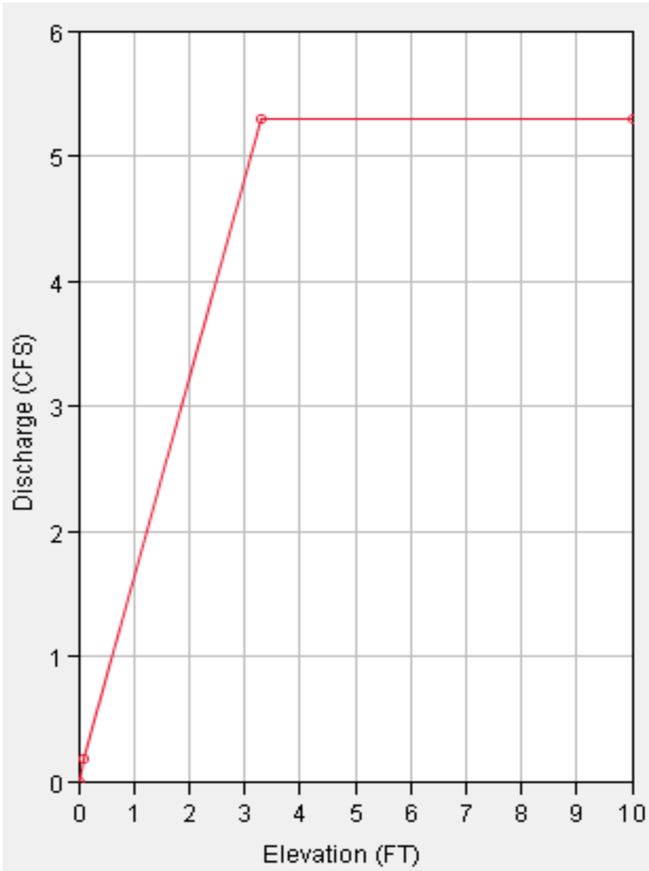

Figure 3.2 - G, Beaver Dam Elevation-Discharge Curve

Finally, the outflow structures allowed for evaporation from the ponds. This calculation was based on the area of the pond at each time step calculated from the elevation-storage curve described above. Monthly evaporation rates were determined using the high altitude pan evaporation rates (section 3.2.3) due to the dam locations in the upper reaches of the watershed.

3.3 Results

3.3.1 Introduction

After the calibration process (section 3.2.3), the calibrated model closely matched the outflow at the stream flow gauge located at the bottom of the watershed (Figure 3.2-B). This outlet was located far from the section of the watershed where junctions were replaced with beaver dams. HEC-HMS however gives information regarding each model element as the water moves through the watershed. Therefore model output was compared at Junction 1552 (J1552) (Figure 3.2-C). This junction was located just downstream of the section containing beaver dams and the outflow from this junction would serve as the location to measure hydrograph changes between the 'dam' and 'no dam' scenarios. After analyzing the effects of beaver dam on the 2012 water year stream flow, two climate scenarios were run to observe the effect of beaver dam on flow on a wetter and drier year.

3.3.2 Calibrated Model Results

The 'no dam' scenario was compared to the observed flow over the 2012 and 2013 water years (Figure 3.3-A). The two years showed variable weather conditions in the Jemez Watershed, and therefore also variable stream flow. In water year 2012, the Jemez Watershed initially had an above average snowpack, but melt out was earlier than usual with northern New Mexico having 44% of normal April snowpack. This early melt out was followed by a below average summer monsoon season (NOAA, 2012). Water year 2013 had low snowpack with 50% of average winter precipitation. This was followed by an abnormally wet summer, with July and September recording the 6th and 2nd wettest months, respectively (NOAA, 2013).

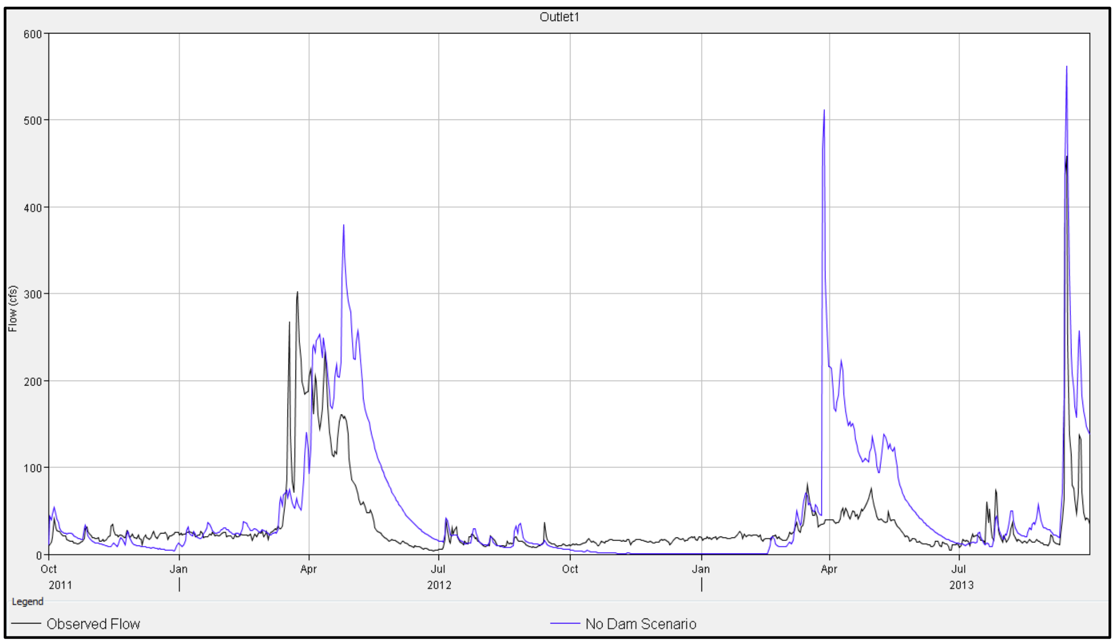

Figure 3.3 - A, 2-Year Calibrated Model Results

The model captured the hydrologic response of the watershed to precipitation events with accuracy. While the peak flow in the first year was a month late, the magnitude was similar. The observed peak was 302 cfs while the modeled peak was 378 cfs. The model also predicted flow response to summer monsoons. The months of July and August 2011 show 5 observed peak flows, all of which are shown in the modeled stream flow on the same days with similar magnitudes. In the summer of 2013, the model under predicted one large flow and over predicted another small flow in July and August. However, the model was able to capture two large September flow events on the same day they occurred.

The observed and modeled hydrographs showed some differences in the timing of the peak flow in year 1 and the magnitude of the peak flow in year 2. The modeled peak occurs on April 25, while the observed occurs a month earlier on March 25. The peak flow in year 2 is significantly higher than the observed flow. Modeled base flow is also low or non-existent during winter months. This issue can be attributed to the difficulty in modeling snow parameters. During the months of November and December, too much precipitation was turned into snow instead of flowing into the stream. The difference in snowmelt can be attributed to several factors. Setting the melt rate is difficult and time limitations prevented the trial and error necessary to perfect these parameters. The model also projects point temperatures measured at temperature stations over broad areas. These projected point temperatures may not represent the variability in temperature of a montane environment.

The model also over-predicted the stream flow by a larger amount in the 2013 water year, which contributed to the large peak flow event. In 2012 the model predicted a total of 45,451,339 m^3 of water through the outlet versus 34,610,267 m^3 of observed flow. This amounted to a 23.9% difference between predicted and observed flow. In 2013 the model predicted a total of 38,019,611 m^3 of water through the outlet versus 23,479,327 m^3 of observed flow. This amounted to a 38.2% difference between predicted and observed flow. The cause of the increase was related to how precipitation inputs were entered into the model. Point rain gauges were used to spread rainfall amounts over a large area and in the 2013 water year the data recorded at the stations was not accurately extrapolated over the watershed area. The additional water combined with the snow modeling problems created the large spring melt-off in water year 2013.

Despite the differences between the observed flow and the modeled flow at the outlet, the model was considered calibrated, given the purpose of this project was to model the effect of beaver dams on peak and summer base flows. Modeling the exact timing of the snowmelt is less important than modeling the correct magnitude of the snowmelt. The magnitude of the melting in the 2012 water year was correct and beaver dams will have a similar effect whether the melting occurs in March or April. Magnitude is also more important when modeling the response to summer storm events, but the model was able to capture both the timing and magnitude of non-snow storm events. The timing of the snowmelt is less important than how the dams affect that melt. While the modeled and observed peak flows occur at different times, their magnitudes are similar enough that how the hydrograph responds to these flows after the beaver dams have been added to the model is a valid set of conclusions that can be drawn from the model.

3.3.3 Beaver Dam Modeling Results

Each dam was given the same parameters, therefore, only one example (Reservoir 1) will be discussed. In reality, each dam's output would be slightly different based on upstream input, but Reservoir 1 illustrates the general output from all of the modeled dams (Figures 3.3-B and 3.3-C).

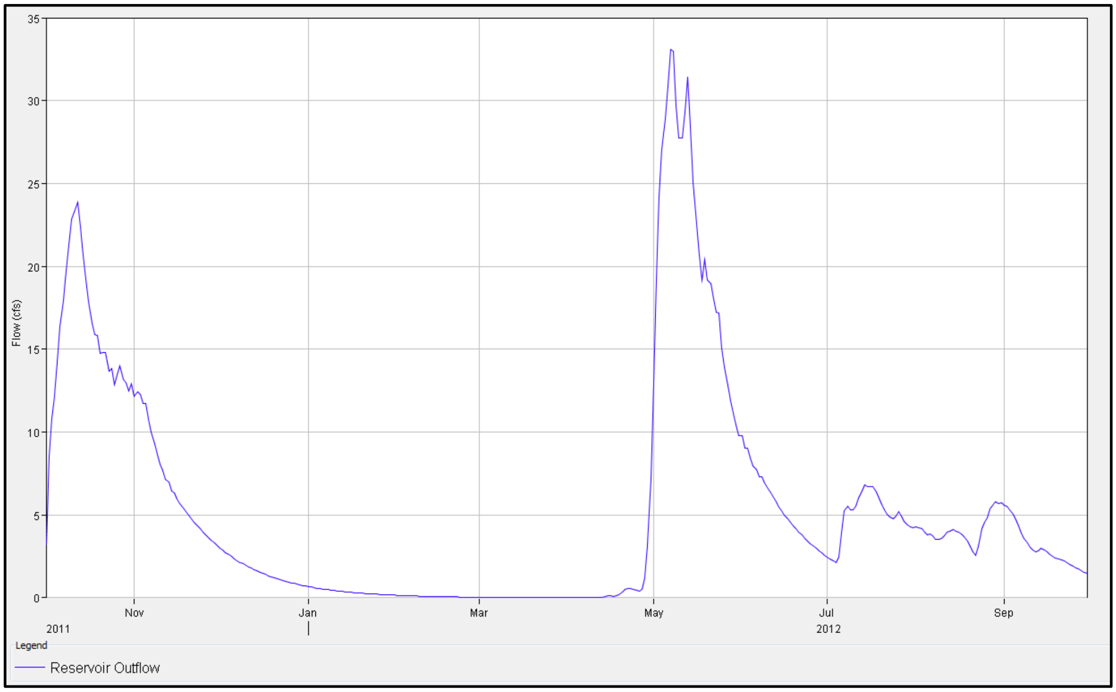

Figure 3.3 - B, Reservoir 1 Outflow

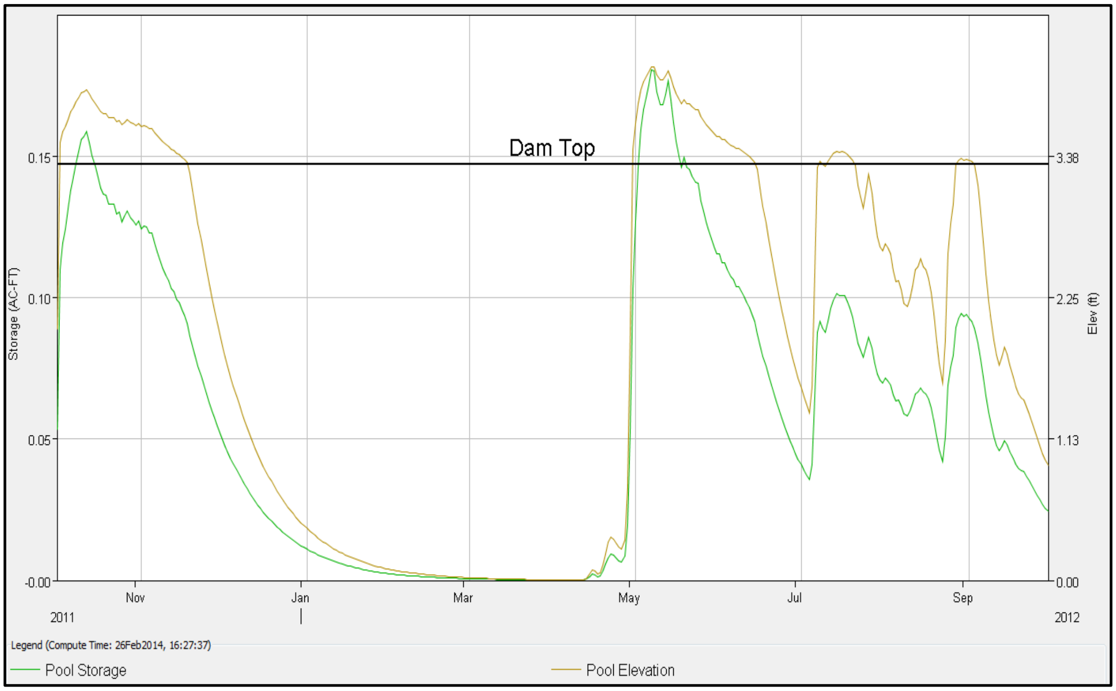

Figure 3.3 - C, Elevation and Storage of Reservoir 1, Water Year 2012

Water can be stored behind the dam, evaporate out of the pond created by the dam, flow over the dam, and seep through the dam. Figure 3.3-B displays the outflow from the dam element. A peak flow occurs out of the dam element during the spring melt event and summer monsoon events. Figure 3.3-C shows the volume of water stored behind the dam and the pond elevation over the 2012 water year. The beaver dam fills initially then drains to 0 over the winter months. This is a result of the previously discussed snow accumulation and melt function errors. The Rio de las Vacas study area is a high elevation river basin that experiences cold winters. In reality, the flow in the river may not ever reach 0, but it will empty and approach 0. The low flow, and the relationship between snow and rainfall in the high elevation basin, is not captured in the model. Therefore stream flow falls to 0, which also acts to empty the beaver pond. It then rapidly fills during the spring melting, increasing both storage and pond elevation. Overtopping of the dam occurs and is shown when the pond elevation is above the dam top line (Figure 3.3-C). After the peak subsides, the pond slowly drains as water seeps through the dam. The storage of water behind the dam and the seepage through the dam are the mechanisms that effect stream flow in the watershed.

3.3.4 Beaver Effect on Stream Flow Hydrology

'Dam' and 'No Dam' Scenarios

After model calibration at the watershed outlet (Figure 3.3-A), it was assumed that outputs from each upstream sub-basin at each junction would also be correctly calibrated.

If the model output was compared at the outlet at the watershed (Figure 3.2-C), the small portion of the sub-basin with modeled beaver dams would have too small of an effect on the modeled hydrograph at the watershed outlet for useful conclusions to be drawn. However, comparing model outputs directly below the beaver dams would allow the dams' effect on the hydrograph to be observed. Therefore, the model was run for the 'dam' and 'no dam' scenarios and the two hydrographs were compared at J1552 (Figure 3.3-D).

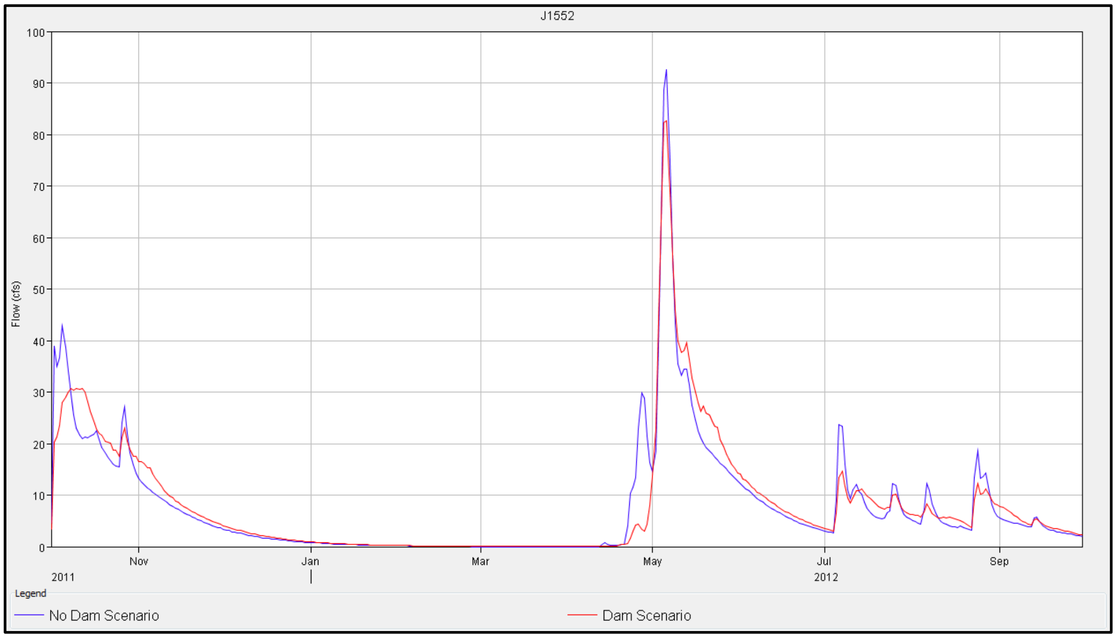

Figure 3.3 - D, Comparison of 'No Dam' Scenario and 'Dam' Scenario at J1552

When viewing the model output at J1552, the lack of baseflow during winter months (section 3.3.2) is more pronounced. Stream flow falls to 0 during the months of January and February and increases when the snow melts in April. This was deemed an acceptable model outcome. There were tradeoffs in modeling seasonal flows in that to accurately capture spring and summer flows simultaneously would have required a manipulation of meteorological parameters that was mutually exclusive between seasons. For example, to accurately capture snow accumulation and melt during winter and spring would have required us to force a percentage of precipitation to fall as water which impacts the accuracy that summer baseflows are modeled. Since the goal was to quantify the impacts of beaver dams on summer baseflows, we chose to use the meteorological parameter values that provided a better fit for summer flows. It is possible that montane streams freeze during the winter, and while documentation whether or not this occurs in the Rio de las Vacas study area, beaver do have the ability to live in cold environments and ponds that are frozen over (Aleksiuk & Cowan, 1969). For modeling purposes, the effect of beaver dam on winter base flow was not an output of interest, therefore, the analysis of the falling limb of the winter snowmelt, peak flow, and summer storm events was deemed sufficient.

These results show a significant effect on the hydrograph from the addition of the 42 beaver dams. The simulated beaver dams attenuate peak flows associated with snow melt and monsoonal rain and increase flow during the falling limbs of these peaks.

The initial analysis was performed on the spring peak flow and subsequent falling limb. Peak flow at J1552 occurs on May 6 with a flow of 92.5 cfs, which was reduced to 82.7 cfs in the 'dam' scenario. The 9.8 cfs difference represents an 11% reduction in peak flow and is the greatest difference along the falling limb. The falling limb from this peak flow occurs from May 7 to July 4 with one intermediate peak. Over this falling limb, the beaver dam model results have on average 2.2 cfs more flow than the 'no dam' scenario. As the spring melt subsides and subsurface baseflow becomes the dominant source of water to the streams, significantly increases baseflow by 20%.

Similar results are seen during the summer monsoonal peak flows. The summer monsoons displayed 4 peak events and with corresponding falling limbs from that peak flow. All 5 peak flow events showed significant reductions in peak flow and an increase of average falling limb flow (Table 3.3-A). These results are shown under the original precipitation column, while the other two columns show results from climatic scenarios discussed below.

Table 3.3 - A, Beaver Dam's Effects on Stream Hydrology

Flow Event	Duration	Original Precipitation		75% Summer Precipitation		125% Summer Precipitation	
		Peak Flow Reduction (cfs)	Falling Limb Flow Increase (cfs)	Peak Flow Reduction (cfs)	Falling Limb Flow Increase (cfs)	Peak Flow Reduction (cfs)	Falling Limb Flow Increase (cfs)
1	May 6 - Jul 4	9.8 (11%)	2.2	n/a	n/a	n/a	n/a
2	Jul 6 -24	10.2 (43%)	0.2	5.2 (33%)	0.4	14.5 (45%)	1.5
3	Jul 26 - Aug 4	1.8 (15%)	0.8	0.6 (1%)	0.4	3.8 (20%)	1.0
4	Aug 6 - 22	3.9 (31%)	0.2	1.6 (28%)	0.2	6.4 (33%)	1.1
5	Aug 24 - Sep 11	6.3 (33%)	0.6	3.4 (33%)	0.4	9.5 (35%)	2.0
6	Sep 13 - 30	n/a	n/a	n/a	n/a	1.7 (16%)	0.6

The model showed that the addition of beaver dams into a stream system reduces peak flow and increases stream flow after peak events. In areas with flashy storm events, such as the Jemez Watershed, water is captured behind the dams and reduces the volume of water downstream. This water is then more slowly released over time as it seeps through the dam.

Climate Scenarios

The model was run simulating two simple climate scenarios. Summer precipitation input data (June 1 - September 31) was increased and decreased by 25% to observe the beaver dams' effect on flow in a wetter and drier year. Only summer precipitation was manipulated due to the difficulty of modeling snow accumulation and melt (section 3.3.2).

The 'dam' and 'no dam' scenarios were run with the new precipitation data (Table 3.3-A). Because only the summer precipitation was manipulated, the spring peak flow event (flow event 1) remained the same and therefore the data were not input to Table 3.3-A. Additionally the 125% precipitation scenario created a 6th peak flow event on September 13. This peak flow event can be seen in the original hydrograph (Figure 3.3-D) but was excluded from the analysis because the flow increase in the original and 75% scenarios was too small for an effect to be observed. Increasing the precipitation by 25% made this peak flow event more visible, and it was included in the analysis for this scenario.

Under the two climate scenarios, the beaver dams have the same effect of decreasing peak flow events and increasing falling limb base flow. Under the 125% precipitation scenario, beaver dams reduce peak flow more effectively (2-5%) than the normal precipitation year. Under the 75% precipitation scenario, beaver dams reduce peak flow less effectively (0%-15%) than during the normal year. During the 75% precipitation scenario the peak flow is attenuated less because the beaver dams never reach their full storage capacity. During the 125% precipitation scenario the dams reach their maximum storage capacity for the majority of the summer season and any increase in water input beyond this amount will have a diminished attenuating effect. Therefore there is an upper limit to the level of peak flow attenuation provided by beaver dams caused by storage limitations behind the dams.

4.1 Introduction

The environmental engineering capabilities of the North American beaver are well understood and documented, however effects of dam building had not been examined in arid ecosystems until recently (Pollock et al., 2003; Pollock et al., 2004; Bird et al., 2011; Wild, 2011; Gibson & Olden, 2014). These effects include the creation of ponds in the river system through dam building, regularly feeding on a variety of riparian plant species, and interacting with other organisms within the ecosystem, leading to additional changes in the ecosystem. Using the results of the beaver capacity evaluation (Chapter 2) and hydrologic modeling (Chapter 3) in combination with a literature review, the re-establishment of beaver to the Jemez Watershed was investigated in an ecosystem assessment with particular focus on the increase of aquatic and riparian habitat to potentially support special-status species.

4.2 Methods

4.2.1 Beaver Impacts on Aquatic and Riparian Ecosystems

A formal review of peer-reviewed literature was conducted focusing on research that would be most relevant to the target study area of beaver impacts on aquatic and riparian habitat creation and ecosystem dynamics. Results from standardized keyword searches in Google Scholar, ScienceDirect, and JSTOR were screened by title, abstract, and full text to identify papers that met a certain criteria. The criteria consisted of 3 main points: (1) peer-reviewed journals published in English-language; (2) relevant to the ecology and management of beaver populations in dryland ecosystems; and (3) relevant to special-status species, in particular salmonid fish species, and interactions with beaver dams and ponds in dryland ecosystems. The literature was synthesized to extract key principles of beaver impacts on aquatic and riparian ecosystems and then applied to the Jemez Watershed based on beaver capacity (Chapter 2) and hydrologic modeling (Chapter 3).

4.2.2 Ecological Modeling

In order to frame the analysis of ecosystem change due to beaver re-establishment in the Jemez Watershed, a simple ecological model was built to provide an assessment of the impact of beaver on flooded area and riparian habitat. The model calculated the number of beaver colonies and number of individual beaver expected in the Jemez Watershed. To accomplish this, the model used the dam density outputs from the BRAT model (Chapter 2), scaled to appropriate capacity.

Aquatic and Riparian Habitat

The first modeling step was to construct each dam represented in the outputs from the BRAT model. Each dam was given several characteristics, which were randomly generated from a realistic range of possible values, determined from literature review (Beedle, 1991; Gurnell, 1998; J. Wheaton, personal communication, 2013). Each dam was given a height (range = 0.8 to 1.2 m), a porosity (range = 0.5 to 0.95), and a width (range = 3 to 5 m). The porosity value allowed calculation of the dam's "effective height", a measure of the true height of the water behind the dam, in relation to the height of the top of the dam:

$$\textit{Effective Height} = \textit{Dam Height} * \textit{Porosity} \qquad \text{(EQ 5)}$$

Because porosity was set up as a measure of the dam's retentive capacity (e.g. 1= full retention, 0 = no retention), this measure scaled the water height down from the top of the dam based on how much was allowed to flow through the structure itself.

Knowing the slope of the stream behind the dam (as an input and output of the BRAT model), simple geometry was used to calculate the surface area of the flooded area behind each dam. This was cumulated for the entire Jemez Watershed, and performed at 10% dam capacity increments, from 10% to 100% capacity.

The next modeling step was to generate an estimate for the amount of riparian habitat that the beaver ponds would create. Knowing the length of each beaver pond from the previous modeling step, a "riparian corridor" next to each beaver pond was constructed. The width of each corridor was randomized from a range of 20 m to 30 m from the edge of the stream. This range was chosen based on the parameters of the BRAT model, which assumes that beaver preferentially forage 30 m away from their pond. The lower end of 20 m was chosen to add a conservative element to the analysis. The slope of the bank next to beaver dams and their ponds was randomized from a range of 0.001 to 0.01. These numbers were chosen because they represent the prime foraging distance for beaver from their ponds, as used in the BRAT model. While it is possible that riparian habitat can extend beyond this range, the focus of this analysis remained within the chosen range parameters.

Beaver Colonies and Individuals

The model constructed a range of possibilities for the number of individual beaver and beaver colonies in the Jemez Watershed. Gurnell (1998) reported that a beaver colony will build an average of 2 to 3 dams and that each colony may consist of 2.7 to 6.2 beaver, based on field surveys. This information is approximately echoed in Beedle

(1991) and Nyssen et al. (2011). Using simple calculations, a range of beaver colonies and individual beaver was constructed over the capacity steps.

4.2.3 Database Search of Special-Status Species

In order to assess the impact of beaver specifically in the Jemez Watershed, the Biota Information System of New Mexico (Bison-M) was used to search for wildlife species with federal or state special-status designations, including threatened, endangered, sensitive, or candidate statuses, that are known to occur within the watershed. Bison-M was searched for special-status species known to occur within Sandoval, Los Alamos, and Rio Arriba Counties. The search was further refined to identify special-status species that inhabit riparian and aquatic habitats for al or part of their lifecycle, thus creating a list of special-status species that may occupy habitat created or influenced by dam building beaver.

4.3 Results

4.3.1 Beaver Impacts on Aquatic and Riparian Habitat

Aquatic Habitat

By the nature of their dam building activities, beaver impound water in rivers, creating ponds. In addition to the hydrologic effects of beaver ponds discussed in Chapter 3, these ponds impact habitat that is suitable for lotic fish populations. Beaver ponds typically have slow current velocities and large surface areas, which provide for productive habitat for fish. In beaver ponds, fish prefer less agitated water, increased invertebrate and forage fish densities, specific temperature conditions, and protection from invasive fish species.

Temperature Regulation. In one representative study of beaver dams and their impacts in Sagehen Creek, California, Gard (1961) investigated the temperature in a series of beaver ponds. The results indicate that temperatures along a depth gradient in the pond in winter showed little variation. However, temperatures in the summer showed a strong gradient, with temperature differences up to 3.3ºC. Salmonid fish species are temperature sensitive (USFS, 2006), so temperature regulation in beaver ponds has strong implications for trout habitat because the cool lower layer of water in the pond could be used as a refuge for trout during hot summer days. Additionally, Gard (1961) found that the temperature of water entering a pond is significantly decreased by the time the water leaves the pond. This has potential implications for further control of temperature downstream of reaches inhabited by beaver, allowing salmonids to spread from their current habitat by creating new reaches with suitable temperatures for spawning and over-summer survival.

Sediment Collection. Studies suggest that beaver could have an impact on fish populations by increasing fine sediment load in stream areas behind dams and reducing the availability of redds for trout (Pollock et al, 2003). However, Pollock (2003) suggests that these studies are often subjective and anecdotal. Beaver have the potential to generally reduce sediment loading in a stream and improve sediment loading/remediate siltation of redds downstream of their habituated zones by accumulating sediment behind dams and preventing its movement past the pond (Leidholt-Bruner, Hibbs & McComb, 1992). This is likely particularly relevant in burn areas, or area with high, naturally driven, fire regimes such as the Jemez Watershed because high sediment loads can be expected from fire-affected hillslopes.

Fish Assemblages and Sizes. For salmonids, studies show that reaches where beaver are present produce more or larger fish, or both (Cook, 1940; Gard, 1961; Pollock et al., 2003; Pollock et al., 2004). In addition, diversity and biomass of other fish species is typically increased (Leidholt-Bruner et al., 1992; Keast & Fox, 1990; Snodgrass & Meffe, 1998). This is important because many of these species, such as the three spined stickleback, are food species for salmon and trout populations. Hanson and Campbell (1963) showed that beaver ponds had a greater biomass of fish compared to areas without ponds. Snodgrass and Meffe (1998) concluded that first and second order streams showed higher response to these phenomena, which is particularly applicable to the Jemez Watershed where many of the stream reaches predicted to support beaver dams are of the first and second order (Chapter 2). Finally, Schlosser (1995) states that beaver ponds in headwater streams provide sources for fish populations, both trout and forage fish, that can then spread into adjacent reaches which act as sinks for these fishes.

Beaver Dams as Barriers. Many species of fish pass both up and downstream of beaver dams, except at low flows (Schlosser, 1995). However, Lotkeff, Roper, and Wheaton (2013), found that this was not the case while studying native and non-native trout movement in Utah streams. Specifically, after tagging well over 1,000 trout, Lotkeff et al. (2013) found that beaver dams generally did not impede movement but that native cutthroat were much more likely to pass a dam than the invasive brown trout. This has implications for the management of native trout populations because of the potential for detrimental hybridization of the natives. Spawn timing largely mediated passage, where natives were better adapted to pass dams when higher flows occurred. Non-native species were less adept and often tried to pass during low-flow conditions.

Riparian Habitat

As beaver ponds fill with water, the flooded area spreads across the landscape, expanding the aquatic habitat available, as described previously. As the flooded area increases, so does the area that becomes saturated around the ponds. This surrounding area then provides space for riparian habitat due to its immediate proximity to freshwater. The riparian zone in dryland ecosystems is typically characterized by vegetation such as willow (*Salix* spp), aspen and cottonwood (*Populus* spp), and a diverse herbaceous understory that requires more water availability than other upland vegetation types in the watershed. Terrestrial wildlife such as birds, mammals, amphibians, and insects benefit from this riparian habitat provided by beaver ponds. This riparian habitat is the source of greater biodiversity in dryland systems when compared to upland areas and is thus an important ecosystem for species that require riparian habitat in dryland systems (Gibson & Olden, 2014). Because beaver live in dryland ecosystem streams and forage for woody and herbaceous plants in the adjacent habitats for food and dam construction, the impacts of beaver on this habitat were further investigated.

In dryland systems, beaver typically use riparian trees such as cottonwood or willow from the riparian zone adjacent to the dam site for food and dam construction (Gibson & Olden, 2014). The ponding effects of beaver dams also provide a greater water source for riparian vegetation growth such as rushes (Juncaceae) and sedges (Cyperaceae) (Call, 1970; Hall, 2005). As beaver dams fill with sediment over time, beaver meadows and wetlands form behind the dam (Burchsted, Daniels, Thorson & Vokoun, 2010). These meadows and wetlands provide habitats for other wildlife species, such as the New Mexico meadow jumping mouse (*Zapus hudsonius luteus*; Frey & Malaney, 2009), songbirds including the southwestern willow flycatcher (*Empidonax traillii extimus*; Johnson, 2011), amphibians, invertebrates, and fish species (Gibson & Olden, 2014). While traditional beaver meadows are unlikely in dryland streams due to the flashy nature of storm events frequently damaging or destroying dams (Andersen & Shafroth, 2010), exposed sediments from secondary channel building or breached ponds are favorable for willow and riparian vegetation establishment (Apple, 1985; Cooper, Dickens, Hobbs, Christiansen & Landrum, 2006; Demmer & Beschta, 2008).

While beaver ponds create suitable habitat for riparian vegetation and associated species, beaver also forage and remove riparian vegetation. Beier and Barrett (1987) found that beaver foraging lead to local extinction of aspen and cottonwood stands but willow species were resilient and actually benefited from beaver foraging. Similarly, Breck, Wilson, and Andersen (2001) determined that beaver herbivory promoted willow species and negatively impacted cottonwood species. The USFWS (2002) recommends beaver be used for southwestern willow flycatcher conservation as the species requires dense stands of willows; however, Finch and Stoleson (2000) suggest that beaver may actually be harmful to the conservation of southwestern willow flycatcher due to their active herbivory of willow stands. This dynamic system of riparian habitat creation and herbivory requires a closer quantitative analysis to determine if beaver have a net positive or negative impact on arid riparian ecosystems. Such analysis was out of the scope of this project.

4.3.2 Ecological Modeling

Aquatic and Riparian Habitat

Beaver and their dams exhibit a diverse range of characteristics both physically and temporally. This analysis served as an estimate of beaver impact on aquatic and riparian habitat in the Jemez Watershed.

The ecological model estimated the area of aquatic and riparian habitat that would be created as a percentage of beaver dam maximum capacity within the watershed (Figure 4.3-A). The relationship between the calculated quantities and the percentage of maximum capacity is not linear. The non-linear relationship is a consequence of handling fractional dam density predictions as probabilities (section 2.2.2). It is also, to a lesser degree, due to the randomization inside the ranges established (section 4.2.2). As the capacity is scaled back, the proportion of reaches where the number of beaver dams is a fraction of 1 increase, which increases the probability of having reaches with no dams. This, in turn, increases the probability of having no additional flooded area or riparian habitat from a dam, thus the downturn in values around 60% capacity.

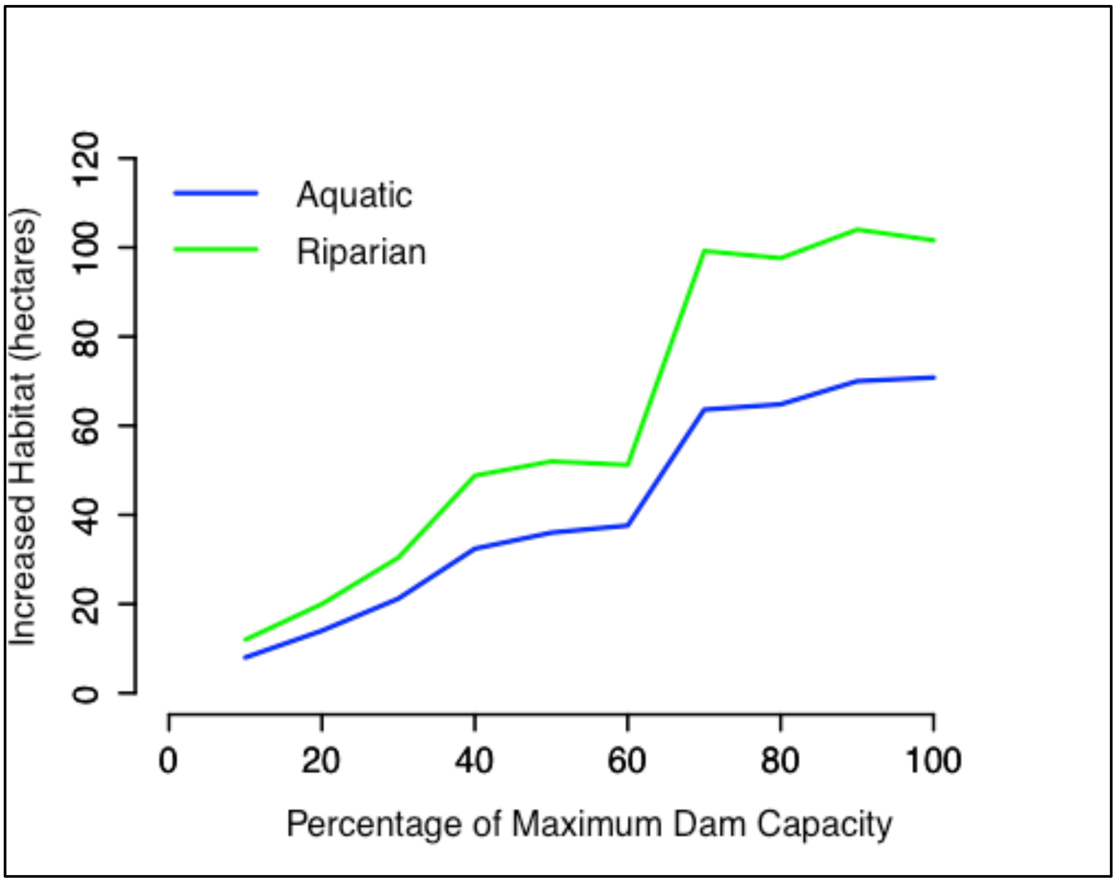

Figure 4.3 - A, Area of Aquatic and Riparian Habitat as a Percentage of Maximum Capacity

Numerical results for all the trial runs at differing percentages of full capacity are reported in Table 4.3-A. 'Aquatic' represents the additional surface area of aquatic habitat to be expected from beaver and 'Riparian' represents the extent of riparian corridor creation along the margins of beaver ponds in the watershed.

Table 4.3 - A, Trial Run Results

Capacity (%)	Flooded Area (hectares)	Riparian Habitat (hectares)	# Colonies (Low)	# Colonies (High)	# Beaver (Low)	# Beaver (High)
10	8	12	170	255	459	1541
20	14	20	324	487	876	3019
30	21	31	497	746	1342	4625
40	33	49	790	1185	2133	7350
50	36	52	850	1276	2296	7911
60	38	52	892	1339	2412	8301
70	64	100	1499	2249	4049	13947
80	66	99	1577	2366	4258	14669
90	71	105	1640	2461	4429	15258
100	72	103	1607	2413	4343	14961

Beaver Colonies and Individuals

The ecological model was used to determine a range of beaver colonies and individuals as a percentage of maximum dam capacity. Both numbers of colonies and numbers of individual beaver increase as dam density increases. At maximum dam capacity, it is estimated that approximately 1,607 to 2,413 beaver colonies may exist in the Jemez Watershed (Figure 4.3-B). This amounts to a potential range of 4,343 to 14,961 individual beaver (Figure 4.3-C). Table 4.3-A illustrates the number of beaver colonies and number of individual beaver expected in the Jemez Watershed after different runs at capacity intervals.

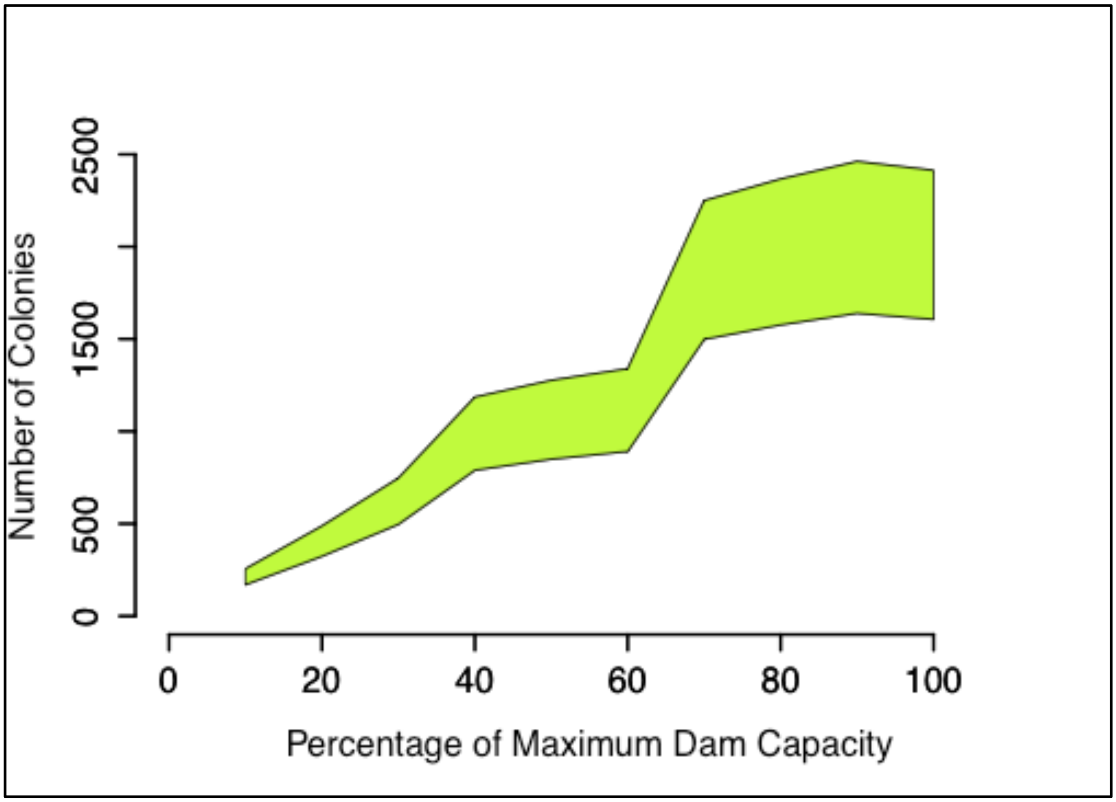

Figure 4.3 - B, Number of Beaver Colonies as a Percentage of Maximum Capacity

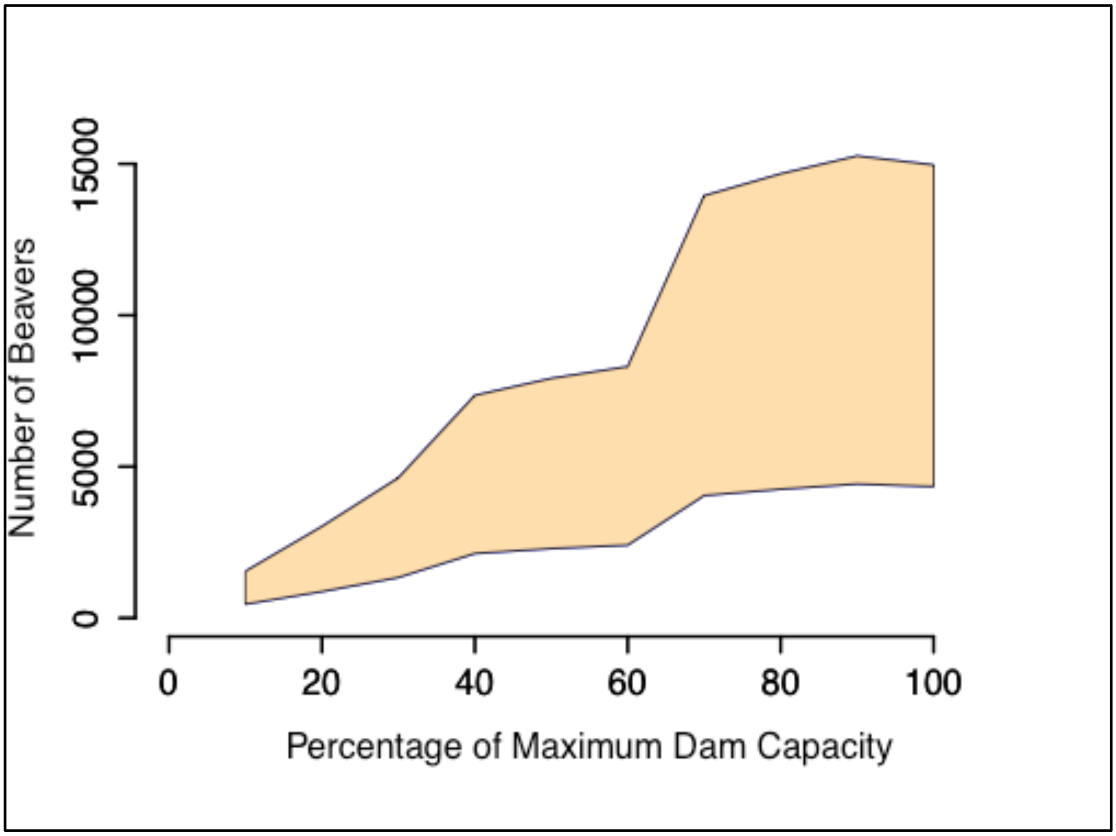

Figure 4.3 - C, Number of Beaver as a Percentage of Maximum Capacity

4.3.3 Special-Status Species Known to Occur within the Watershed

The Bison-M database search resulted in a list of 53 special-status species known to occur within Sandoval, Los Alamos, or Rio Arriba Counties, which comprise the watershed. The list of species was refined to include only those species that inhabit aquatic or riparian habitat, for all or part of their lifecycle. Thirty-eight (38) upland species were removed from the list and 15 aquatic or riparian species (3 fish, 2 amphibians, 3 birds, 4 mammals, and 3 mollusks) were identified as having the potential to be directly impacted as a result of dam building beaver in the Jemez Watershed (Table 4.3-B). The Rio Grande cutthroat trout (*Oncorhynchus clarkii virginalis*) and New Mexico meadow jumping mouse (jumping mouse; *Zapus hudsonius luteus*) were carried forward for further analysis.

Table 4.3 - B, Special-Status Species Known to Occur within Aquatic or Riparian Habitats in the Jemez Watershed

Common Name	Scientific Name	Status	Habitat
Fish			
Chub, Rio Grande	*Gila pandora*	State NM: Sensitive taxa (informal)	pools of small to moderate streams near areas of current in association with undercut banks, overhanging bank vegetation, and aquatic plants
Minnow, Silvery, Rio Grande	*Hybognathus amarus*	Federal: Critical Hab. Designated (NM) Federal: Endangered State NM: Endangered	shallow, low velocity eddies formed by debris piles, pools, debris stretches, oxbows, and backwaters with silt bottoms
Trout, Cutthroat, Rio Grande	*Oncorhynchus clarkii virginalis*	Federal: Candidate State NM: Sensitive taxa (informal)	small, swift-running, clear cold streams with deep pools and undercut banks
Amphibians			
Salamander, Jemez Mountains	*Plethodon neomexicanus*	Federal: Critical Hab. Designated (NM) Federal: Endangered State NM: Endangered	moist soils in woodlands
Toad, Boreal	*Anaxyrus boreas*	Federal: FWS Species of Concern State NM: Endangered	marshes, wet meadows, streams, beaver ponds, glacial kettle ponds, and lakes interspersed in subalpine forest between 8,000-11,500 feet

Birds			
Cuckoo, Yellow-billed	*Coccyzus americanus occidentalis (western pop)*	Federal: Proposed State NM: Sensitive taxa (informal)	riparian woodlands of willows, cottonwoods and dense stands of mesquite along streams and marshes
Eagle, Bald	*Haliaeetus leucocephalus alascanus*	State NM: Threatened	lakes, reservoirs, rivers, marshes, and coasts
Flycatcher, Willow, Southwestern	*Empidonax traillii extimus*	Federal: Critical Hab. Designated (NM) Federal: Endangered State NM: Endangered	moist, shrubby areas, often with standing or running water
Mammals			
Myotis, Arizona	*Myotis occultus*	State NM: Sensitive taxa (informal)	wooded riparian areas in desert areas
Myotis, Small-footed, Western	*Myotis ciliolabrum melanorhinus*	State NM: Sensitive taxa (informal)	relatively arid wooded and brushy uplands near water
Bat, Spotted	*Euderma maculatum*	State NM: Threatened	arid regions, desert scrub, and open forest in rugged landscapes associated with a water source including springs, creeks, rivers or lakes
Mouse, Jumping, Meadow	*Zapus hudsonius luteus*	Federal: Proposed State NM: Endangered	meadows, fields, forest clearings and edges; the edges of swamps, marshes, and bogs

Mollusks			
Paper Pondshell	*Utterbackia imbecillis*	State NM: Endangered	headwaters, moderate to large streams, large rivers, reservoirs and small ponds with fine substrates and lotic systems with pools, backwaters and other microhabitats where silt and sand are abundant
Mountainsnail, Socorro	*Oreohelix neomexicana*	State NM: Sensitive taxa (informal)	igneous-rock talus and limestone in variety of habitats
Marshsnail, Wrinkled	*Stagnicola caperata*	State NM: Endangered	wetlands, primarily inhabiting vernal ponds, weedy ditches, and the shallow margins of rivers and lakes

Source: Bison-M

Rio Grande Cutthroat Trout

The Rio Grande cutthroat trout is a New Mexico state species of special concern. It is a subspecies of cutthroat trout that historically occurred throughout the southern Rocky Mountains, particularly in southern Colorado and northern New Mexico, but has been extirpated from much of its range (Figure 4.3-D). Within the last two centuries the species population has declined and now only approximately 200 populations are known to exist, the majority of which are confined to headwater streams on USFS land (USFS, 2006). The current population is stable but requires active management due to threats from nonnative trout species invasion and hybridization in addition to human habitat conversion and land uses such as grazing.

As discussed in section 4.3.1, beaver dams and pond environments are known to provide habitat for salmonid species. To determine how beaver may affect the Rio Grande cutthroat trout core populations in the upper Jemez Watershed (Figure 4.3-D), the BRAT maximum dam density output was overlaid onto the stream network within the sub-basins with known occupancy of Rio Grande cutthroat trout (Figure 4.3-E). The ‘frequent’ and ‘pervasive’ categorizes signify the most suitable habitat while the least suitable habitat represent the ‘none’ to ‘occasional’ categories.

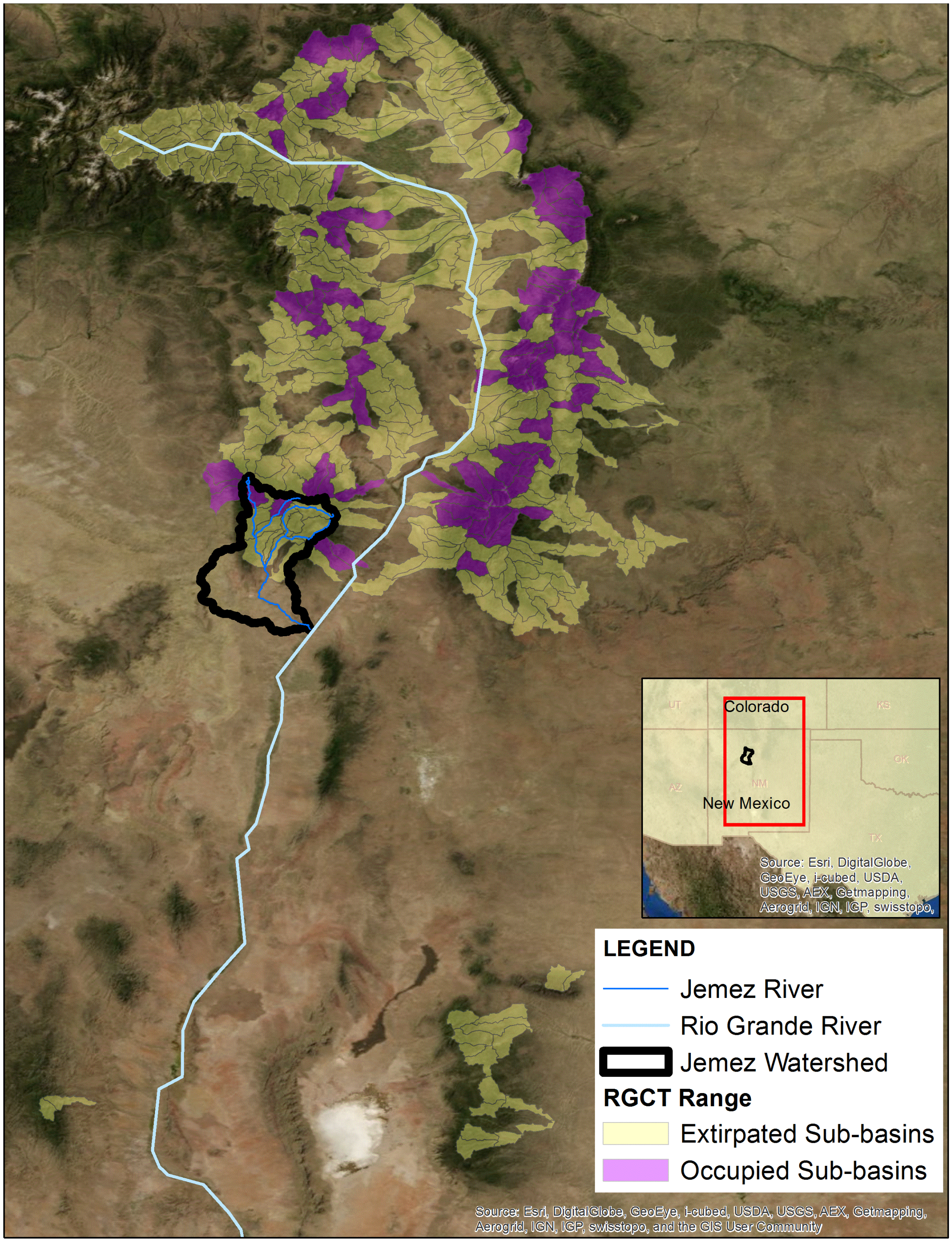

Figure 4.3 - D, Known Range of the Rio Grande Cutthroat Trout

Source: Trout Unlimited, 2014

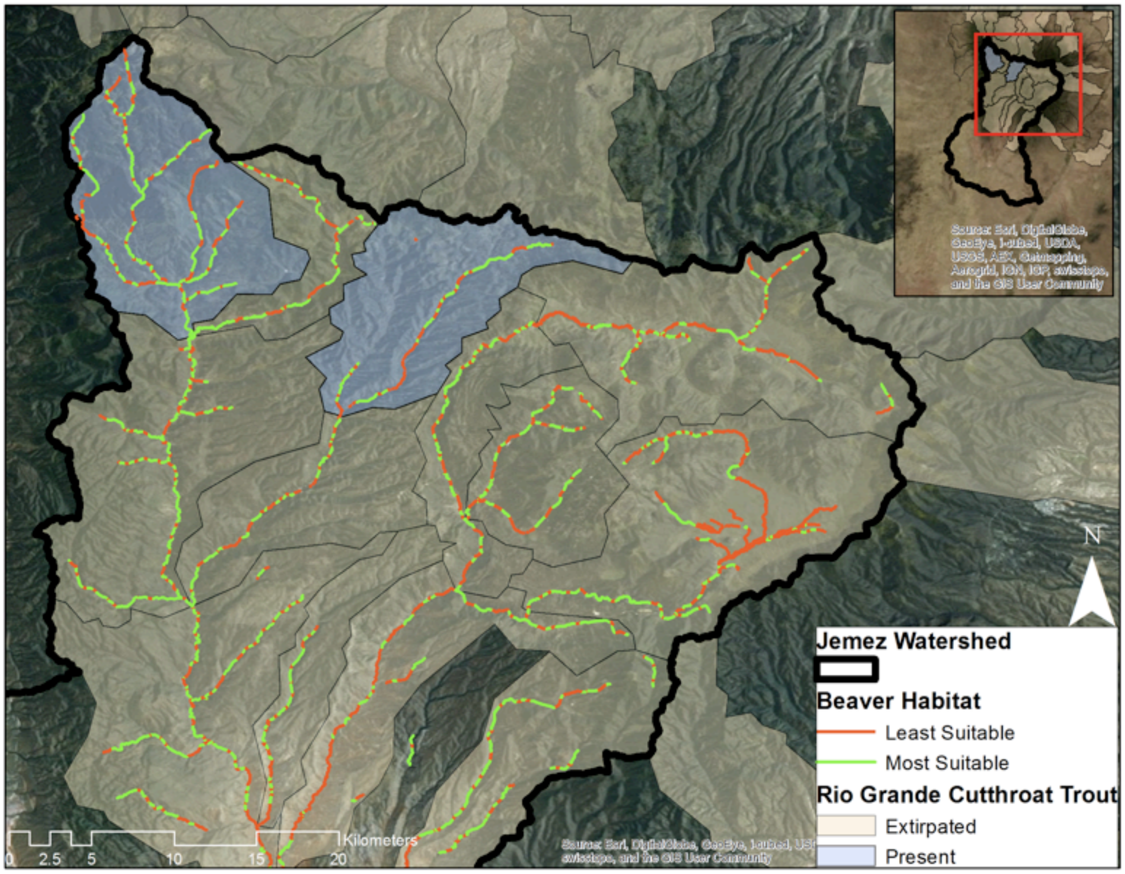

Figure 4.3 - E, Beaver Dam Capacity and Rio Grande Cutthroat Trout Range

From this evaluation, it was determined that suitable dam building habitat can be found within the sub-basins that support the trout population. The USFS (2006) Rio Grande cutthroat trout population assessment for the state of New Mexico suggested a management strategy for restoring and protecting current populations through the construction of 1 m high dams. The goal of the dams would be to create ponds for fish habitat as well as reduce flow of invasive species upstream. Because beaver build dams with an average height of 1 m (Beedle, 1991; Gurnell, 1998), beaver could potentially be used in lieu of artificially constructed dams for trout management. It is also possible that through the re-establishment of beaver to the Jemez Watershed that the Rio Grande cutthroat trout could expand from their current range into sub-basins within their historical range. Further field research would be needed to test this hypothesis.

New Mexico Meadow Jumping Mouse

The New Mexico meadow jumping mouse is a state-endangered species and is proposed for federal listing. It is a semi-aquatic mammal found primarily in riparian habitat along the banks of southwestern streams where it forages for seeds and burrows into the stream banks for protection and winter hibernation (USFWS, 2011). In June 2013, the USFWS proposed 310.5 linear km, or 5,892 hectares, of critical habitat for the jumping mouse within 8 units in Arizona, Colorado, and New Mexico (USFWS, 2013; Figure 4.3-F). Unit 3 falls within the Jemez Watershed and comprises 55.5 linear km, or 1,117 hectares, of three stream reaches. Two (2) reaches are currently occupied and 1 is partially occupied by the jumping mouse.

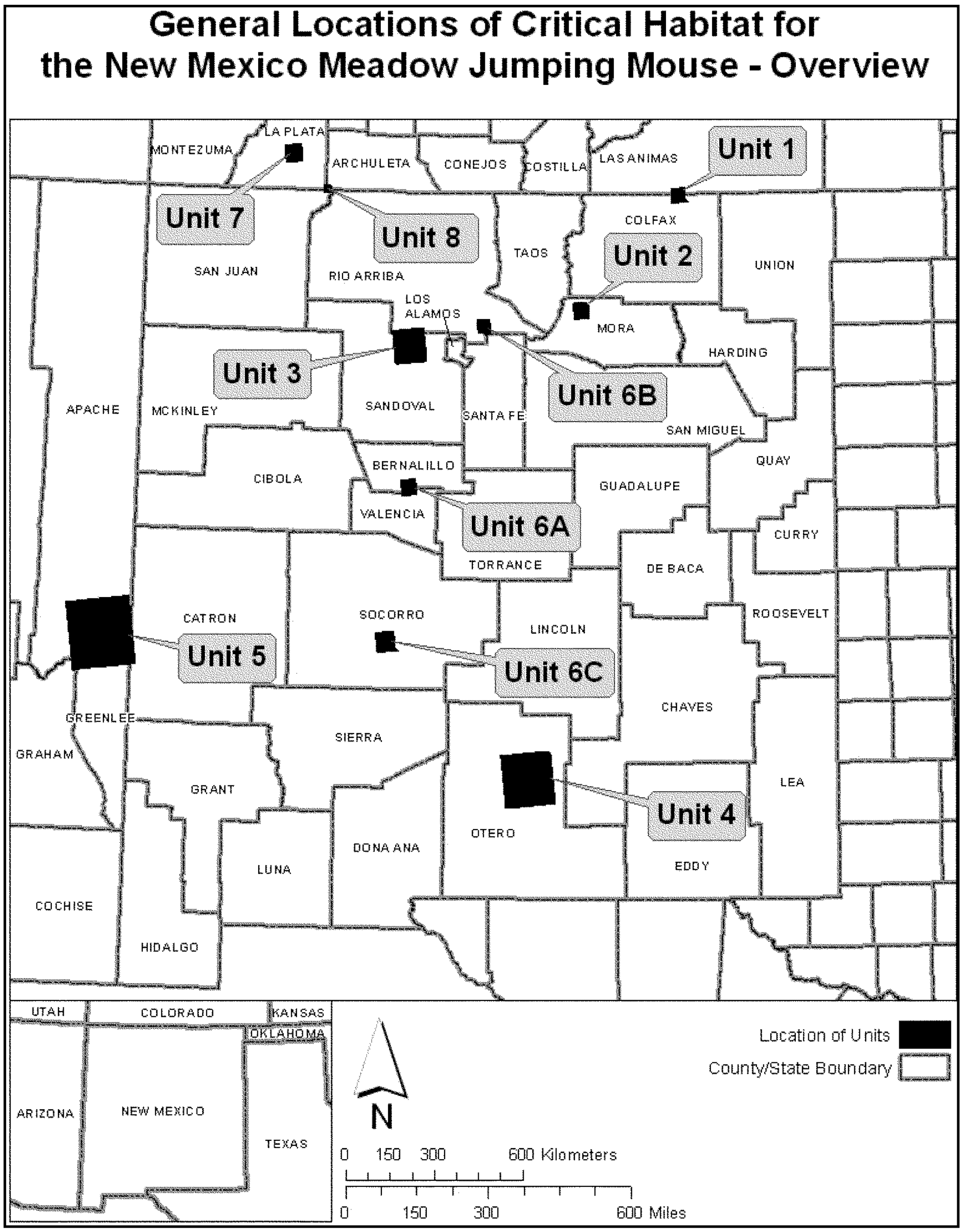

Figure 4.3 - F, USFWS Proposed Critical Habitat Units

As discussed in section 4.3.1, beaver dams and pond environments are known to provide riparian habitat, which is ideal for the jumping mouse for foraging, protection, and hibernation. To determine how beaver may affect the jumping mouse within the Jemez Watershed, the BRAT maximum dam density output was overlaid it onto the stream network within the proposed critical habitat (Figure 4.3-EG). The 'frequent' and 'pervasive' categorizes signify the most suitable habitat while the least suitable habitat represent the 'none' to 'occasional' categories.

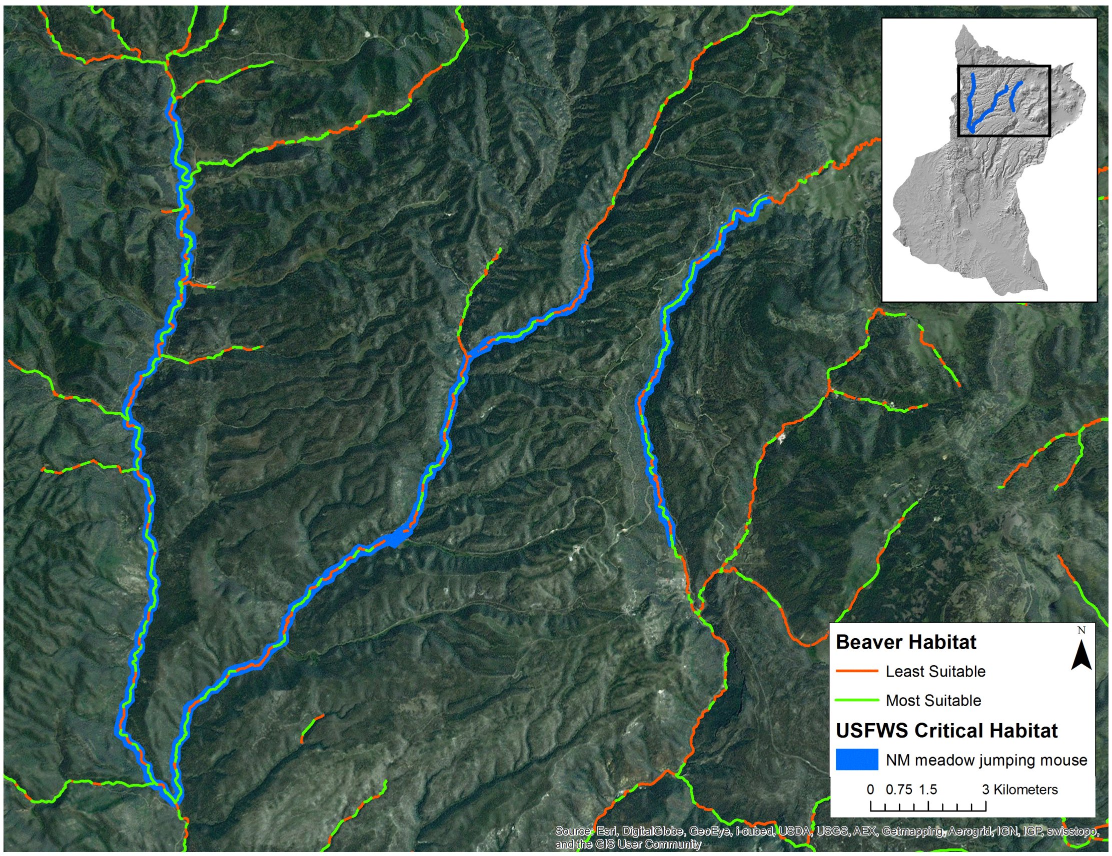

Figure 4.3 - G, Beaver Dam Capacity and New Mexico Meadow Jumping Mouse Critical Habitat

From this evaluation, it was determined that suitable dam building habitat can be found within the proposed critical habitat on stream reaches that currently support the jumping mouse. It is possible that through the re-establishment of beaver to the Jemez Watershed that the jumping mouse could sustain their current population and potentially expand from the currently occupied critical habitat into adjacent riparian habitat associated with beaver dams and ponds within the watershed (Gibson & Olden, 2014). Further field research would be needed to test this hypothesis.

5.0 DISCUSSION

Re-establishing beaver to part of their historic range in the Jemez Watershed has the potential to increase habitat suitability for the region's special-status species through the augmentation of river flows and the creation of aquatic and riparian habitat. Known for their capability as ecosystem engineers, beaver have the ability to alter the environment, through the creation of river obstructions, in a way that could be favorable to other species. However, the same dams that improve habitat for other species are considered by some landowners to be a nuisance. This provides a framework for WildEarth Guardians, land users, and resource managers alike to consider beaver re-establishment in the Jemez Watershed based on evaluating the beaver capacity of the watershed, modeling hydrology, and assessing the ecosystem through aquatic and riparian habitat creation.

5.1 WildEarth Guardians

The client, WildEarth Guardians, is a politically active conservation organization whose primary goals include gathering support for the protection of wildlife populations in New Mexico. Currently, unwanted beaver that are found on private lands can be removed by the landowner either through formal state-mandated removal processes or by an informal removal that is often not coordinated with wildlife officials. The client wants to prevent this informal method of handling nuisance beaver by working towards a statewide beaver management plan for New Mexico.

The client proposed this research project as part of their efforts to investigate the potential impacts of beaver re-establishment in New Mexico. The organization had interest in determining whether dam building activity can be utilized as part of an adaptation strategy against climate change. Water supplies in New Mexico, which are reliant on the volume of snowpack that accumulates during the winter, have the potential to be reduced as climate change impacts progress. Beaver dams have the ability to retard surface flow, which could extend water supplies and affect hydrologic processes. The client wanted to determine whether re-establishing beaver populations in public lands could noticeably affect surface flows downstream.

The measurable impacts of beaver activities on stream flow and timing could be used as supporting evidence of the potential benefits of beaver management, thus making a stronger case for the development of a beaver management plan. Prior to the start of the project, WildEarth Guardians had determined through their own research a number of additional effects of beaver dam building activity that could be available which include augmentation of stream flow, sediment attenuation, and aquatic habitat creation (Bird et al., 2011) provides evidence that can be used to support beaver protection and management and the client wanted the group to investigate the extent of these impacts should beaver be re-established in the Jemez Watershed.

Should a beaver management plan be implemented in the state of New Mexico, it can be a means of ensuring that nuisance beaver are not unnecessarily killed and can be relocated on public lands where their activities do not directly affect landowners.

5.2 Land Users

Regions with arid climates and limited water resources often find themselves in the predicament of how to equitably distribute water between agricultural, municipal, and environmental uses, setting the stage for a potential conflict of interest. In the Jemez Watershed, undeveloped wilderness dominates the landscape in the upper reaches and headwaters, while human development is mostly confined to the more desirable land of the alluvial floodplain in the lower watershed. Given the distribution of land use, a foreseeable outcome would be one where beaver are re-established in the headwaters, providing habitat for species in the area and augmenting flow for downstream water users, without directly interfering with farming and ranching operations. This is in line with the output of the BRAT model, which predicts more suitable beaver habitat among the steeper, vegetated slopes of the watershed away from human development (Chapter 2).

As the group's hydrologic model suggests, beaver dams can extend flow volume and timing later into the season as indicated by hydrograph attenuation, providing benefits for land users. First, any increase in surface water later into the summer means that water users can avoid pumping costs associated with groundwater later into the summer. Second, because beaver dams have been shown to attenuate peak flows associated with storm events (Chapter 3), it is possible that beaver can lessen the risk of flood from the summer monsoonal rains, providing an obvious benefit to landowners. Lastly, beaver create habitat for game fish (Chapter 4), particularly the Rio Grande cutthroat trout, which is a major attraction for fishermen, having the potential to boost the local tourism economy.

5.3 Resource Managers

Land in the Jemez Watershed is owned by a variety of stakeholders, several of which have capacities as resource managers. In particular, the USFS and VCNP have vested interests in preserving and enhancing the quality of their land found within the watershed (Figure 1.3-E).

United States Forest Service

The USFS owns much of the land in the northwestern section of the Rio de las Vacas study area (Figure 1.3-D), which the group identified as past, current, and potential future habitat for both beaver and the state sensitive Rio Grande cutthroat trout. Research showed that beaver and their dams created habitat in locations in the Jemez Watershed that could influence the conservation success of this species (Chapter 4). In fact, the

USFS released an assessment of the species and highlighted the potential of artificially enhancing the habitat conditions in the watershed for trout by creating 1 m high structures to impound the flow of water (USFS, 2006). These structures would slow water, allow for potential temperature regulation and create suitable sediment load conditions downstream to enhance the health of cutthroat trout populations. The intention of these projects align almost identically with the traits found associated with beaver dams, a fact that has not gone unnoticed by the USFS. By focusing on beaver re-establishment in the low order streams, such as the Rio de las Vacas study area, resource managers could dramatically improve the spawning and seasonal habitat for the target species. This would allow it to thrive in its current habitat and spread downstream into its historic but extirpated range.

Research identified beaver dams as significant barriers to invasive trout species movement in a stream system while allowing native trout to move more freely, both up and down stream. The USFS has noted the distinct threat of hybridization as a barrier to conservation success for the Rio Grande cutthroat trout. Thus, the re-establishment of beaver colonies in the Jemez Watershed would allow the native trout population to move in the stream and spawn successfully while impeding the movement of non-native trout that could damage the genetic integrity of the native species. Again, landscape alteration by beaver has to the potential to provide the USFS with low cost solutions that both improve habitat quality for state-listed trout species while mitigation the other threats present to the species in the watershed.

The types of landscape alterations that beaver perform along the streams they inhabit also have implications for projects carried out by the VCNP. The VNCP's current projects focus on wetland and landscape restoration, specifically focusing on the restoration of riparian and wetland ecosystems. Proposed actions for these projects include forest thinning, erosion control systems and improvement of riparian zone characteristics in a broad sense. Beaver can achieve significant results towards these goals if they were to be re-established in the region. Furthermore, the cost of using beaver as ecosystem engineers to achieve these goals could potentially be less than traditional engineering solutions.

However, BRAT showed that habitat in the VCNP is not of prime suitability for beaver due to the widespread presence of grasslands, which are not a suitable material with which to build dams (Chapter 2). Due to this, general beaver management in the Jemez Watershed and usage of the species in order to modify habitat for restoration and conservation purposes may be best targeted in the portions of the land owned by the USFS for trout population rehabilitation.

5.4 Policy Implications

On February 19, 2014, the New Mexico state Senate passed State Memorial 4, calling for the design of a beaver management plan for the state. WildEarth Guardians will likely play a role in the framing and development of this plan and the results of this project may be incorporated into this discussion. This project demonstrates that re-establishing beaver into the Jemez Watershed is possible from a biological standpoint and that this re-establishment could have a range of positive effects on the biological health and diversity of the watershed. This provides strong evidence for both the client and New Mexico state legislators to consider the re-establishment of beaver into their native areas and to actively promote management solutions that view beaver as integral to ecosystem function and stream health in the state.

6.0 CONCLUSIONS

6.1 Objective 1: Beaver Capacity Evaluation

The investigation of the Jemez Watershed using BRAT showed that the landscape can support a re-established beaver population. At maximum capacity, 450 km of reaches within the watershed would support beaver, whereas 120 km of reaches were expected to harbor beaver and their dams at the chosen re-establishment capacity (10% maximum capacity). Furthermore, the results showed that beaver would most likely re-established in the northern, montane, and vegetated portions of the watershed.

6.2 Objective 2: Hydrologic Modeling

The hydrologic model (HEC-HMS) indicated that beaver dams have the potential to attenuate peak flows and increase baseflow. A 5-30% attenuation of peak flows and 5-15% increase in baseflow was observed by inputting 10% of the estimated maximum beaver dam capacity in the Rio de las Vacas study area in the Jemez Watershed. These results indicate that beaver have the ability to alter the flow volume and timing of a river, especially in regions with highly suitable habitat.

6.3 Objective 3: Ecosystem Assessment

Beaver are part of a dynamic system with its ecosystem. Beaver utilize riparian vegetation for herbivory and dam construction and create aquatic and riparian habitat. Beaver in the Jemez Watershed are expected to increase aquatic and riparian habitat, which would have the potential to support up to 15 special-status species. Specifically, beaver would create additional suitable pond habitat for the state-sensitive Rio Grande cutthroat trout and their dams would block the upstream movement of non-native trout. It is possible that with beaver re-establishment this native trout species could expand its current range into previously occupied and currently extirpated habitat. Additionally, beaver could create riparian habitat sufficient for the New Mexico meadow jumping mouse to sustain the current population and expand its range into currently unoccupied stream reaches.

7.0 RECOMMENDATIONS

7.1 Beaver Capacity Evaluation

Two specific actions are recommended for further studies to strengthen the BRAT results. First, a systematic field study of the results of the model should be undertaken. Although this would be complicated by near-complete extirpation of beaver populations in the watershed, one could study the streams for historic presence of beaver. This would allow for a basic framing of the BRAT results and could especially be performed in stream reaches of interest to restoration managers and specialists.

Second, several supplemental runs of the BRAT model are recommended to study the impacts of climate or fire regimes in the Jemez Watershed. Because vegetation compositions along the streams could be expected to shift under these conditions and perhaps rather dramatically after large fires, a potential lack of dam building materials could alter the capacity of the watershed to support or continue to support a re-established beaver population. Although this may be captured in the re-establishment capacity scenario (10% of maximum capacity), a more explicit study of these factors would be of interest for the long-term management of beaver along the Jemez River.

7.2 Hydrologic Modeling

The hydrologic modeling should be developed further. The model should be applied to the whole watershed and include different BRAT and climatic scenarios.

It is also recommended that field investigations be performed to better understand the dynamics of water flowing through a beaver dam over an extended period of study, rather than a single storm event. This information is currently lacking.

7.3 Ecosystem Assessment

To fully analyze how a re-established beaver population would impact the Jemez Watershed ecosystem, the assessment should be expanded further to investigate the relationship between habitat creation and habitat loss from beaver herbivory and dam building. Additionally, the species evaluation should be expanded to investigate all 15 special-status species with the potential to occur in aquatic and riparian habitat within the Jemez Watershed. The potential for beaver to create habitat for special-status species may present conservation planning and compensatory mitigation opportunities, which could also be explored for application and use by land and resource managers.

Fire is another aspect of the environment that has far-reaching land use and biological effects. Historical fire suppression combined with ongoing drought in the southwest has created conditions of increased fire risk. Fires can have beneficial aspects, but they also increase erosion from the landscape and stream turbidity. They are an important aspect of the local environment, which must be taken into account due to their effects on the local environment. The Las Conchas Fire (June 2011) swept through northwestern New Mexico, causing widespread vegetation loss and concerns of downstream effects of sediment deposition. Of particular interest is investigating how beaver respond to wild fires. It is recommended that further investigation be undertaken to determine if beaver can be used after fire to increase canopy cover, block sediment from increased upland erosion and runoff into the stream network, or act as an ecosystem restoration tool to recover the landscape after devastating effects of fire.

7.4 Policy and Management Implications

It is recommended that beaver populations be considered for re-establishment in the Jemez Watershed and that the findings from this project be used as supporting information integrated into the mandated statewide beaver management plan.

8.0 REFERENCES

Aleksiuk, M. & McTaggart Cowan, I. (1969). Aspects of seasonal energy expenditure in the beaver (*Castor canadensis kuhl*) at the northern limit of its distribution. *Canadian Journal of Zoology*, 47(4).

Andersen, D.C. & Shafroth, P.B. (2010). Beaver dams, hydrologic thresholds, and controlled floods as a management tool in a desert riverine ecosystem, Bill Williams River, Arizona. *Ecohydrology,* 3, 325–338.

Apple, L.L. (1985) Riparian habitat restoration and beaver. R.R. Johnson et al. (Eds.) *Riparian Ecosystems and Their Management: Reconciling Conflicting Uses*. First North American Riparian Conference. 489-490.

Beedle, D. (1991). *Physical Dimensions and Hydrologic Effects of Beaver Ponds on Kuiu Island in Southeast Alaska* (Doctoral dissertation). Oregon State University, Corvalis, OR.

Beier, P. & Barrett, R.H. (1978). Beaver habitat use and impact in Truckee River basin, California. *The Journal of Wildlife Management*, 51(4), 794-799.

Bird, B., O'Brien, M., & Petersen, M. (2011). Beaver and climate change adaptation in North America: a simple, cost-effective strategy. WildEarth Guardians. Print.

Breck, S.W., Wilson, K.R., & Andersen, D.C. (2001). The demographic response of bank-dwelling beaver to flow regulation: a comparison on the Green and Yampa rivers. *Canadian Journal of Zoology*, 79, 1957-1964.

Burchsted, D., Daniels, M., Thorson, R., & Vokoun, J. (2010). The river discontinuum: applying beaver modifications to baseline conditions for restoration of forested headwaters. *BioScience,* 60, 908-922.

Call, M.W. (1970). *Beaver pond ecology and beaver–trout relationships in southeastern Wyoming* (Doctoral dissertation). University of Wyoming, Laramie, WY.

Cook, D.B. (1940). Beaver-trout relations. *Journal of Mammalogy*, 21(4), 397-401.

Cooper, D.J., Dickens, J., Hobbs, N.T., Christensen, L., & Landrum, L. (2006). Hydrologic, geomorphic and climatic processes controlling willow establishment in a montane ecosystem. *Hydrologic Processes,* 20, 1845-1864.

Demmer, R., & Beschta, R.L. (2008). Recent history (1988–2004) of beaver dams along Bridge Creek in central Oregon. *Northwest Science,* 82, 309-318.

Devito, K.J. & Dillon, P.J. (1993). Importance of runoff and winter anoxia to the P and N dynamics of a beaver pond. *Canadian Journal of Fisheries and Aquatic Sciences*, 50, 2222-2234.

Duishonakunov, M. (2008). *Watershed Parameters Retrieval, Hydrologic and Hydraulic Study of Manali Sub-basin of Beas River, India* (Doctoral dissertation). Kyrgyz National University, Center for Space Science and Technology Education in Asia and the Pacific (CSSTEAP).

Finch, D.M., & Stoleson, S.H. (2000). Status, ecology, and conservation of the southwestern willow flycatcher. USDA Forest Service, Rocky Mountain Research Station, Odgen, UT.

Frey, J.K., & Malaney, J.L. (2009). Decline of the meadow jumping mouse (*Zapus hudsonius luteus*) in two mountain ranges in New Mexico. *The Southwestern Naturalist*, 54, 31-44.

Gard, R. (1961). Effects of beaver on trout in Sagehen Creek, California. *The Journal of Wildlife Management*, 25(3), 221-242.

Gibson, P.P. & Olden, J.D. (2014). Ecology, management, and conservation implications of North American beaver (*Castor canadensis*) in dryland streams. *Aquatic Conservation: Marine and Freshwater Ecosystems*. DOI: 10.1002/aqc.2432

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

Hall, F. (2005). Emigrant Creek cattle allotment: lessons from 30 years of photomonitoring. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Hanson & Campbell (1963). The effects of pool size and beaver activity on distribution and abundance of warm water fishes in a north Missouri stream. *American Midland Naturalist*. 69, 136-149.

Hydrologic Engineering Center (HEC) (1995) *Hydrologic Engineering Center's River Analysis System* (Version 4.1) [Computer program]. Available at http://www.hec.usace.army.mil/software/hec-ras/downloads.aspx (Accessed 19 April 2013).

Hydrologic Engineering Center (HEC) (2010). *Hydrologic Modeling System (HEC-HMS) User's Guide (Version 3.5).* Davis, CA: Army Corps of Engineers.

Hydrologic Engineering Center (HEC) (2014). *Hydrologic Engineering Center*. Retrieved from HEC-HMS: http://www.hec.usace.army.mil/software/hec-hms/

Johnson, G. (2011). *Bird abundance and richness in a desert riparian area following beaver re-introduction* (Doctoral dissertation). University of Arizona, Tucson, AZ.

Keast, A. & Fox, M.G. (1990). Fish community structure, spatial distribution and feeding ecology in a beaver pond. *Environmental Biology of Fishes,* 27, 201-214.

LANDFIRE: LANDFIRE Existing Vegetation Type layer (June 2013). U.S. Department of Interior, Geological Survey. [Online]. Available: http://landfire.cr.usgs.gov/viewer/ [2013,October 5].

Leidholt-Bruner, K., Hibbs, D.E, & McComb, W.C. (1992). Beaver dam locations and their effects on distribution and abundance of coho salmon fry in two coastal Oregon streams. *Northwest Science*, 66(4).

Lotkeff, R.L., Roper, B.B., & Wheaton, J.M. (2013). Do beaver dams impede the movement of trout? *Transactions of the American Fisheries Society*, 142(4), 1114-1125.

MacFarlane W.W. & Wheaton, J.M. (2013). Modeling the capacity of riverscapes to support dam building beaver – case study: Escalante River Watershed. *Ecogeomorphology and TopographicAnalysis Lab*, Utah State University, Logan, UT.

Ming-Ko, W. & Waddington, J.M. (1990). Effects of beaver dams on subarctic wetland hydrology. *Arctic*, 43 (3), 223-230.

National Oceanic and Atmospheric Association (NOAA) (2012). Albuquerque, NM Weather Forecast Office. *2012 Annual Weather Highlights Hydrology/Drought*. at: http://www.srh.noaa.gov/abq/?n=climonhigh2012annual-hydrodrought

National Oceanic and Atmospheric Association (NOAA) (2013). Albuquerque, NM Weather Forecast Office. *2013 Annual Weather Highlights Hydrology/Drought*. Available at: http://www.srh.noaa.gov/abq/?n=climonhigh2013annual-hydrodrought

New Mexico Environment Department. (2013). *Beaver and Wetlands Workshop, Agenda*. 9 May 2013. New Mexico State Library, Room 2027, 1205 Camino Carlos Rey, Santa Fe, NM.

Nyssen, J., Pontzeele, J., & Billi, P. (2011). Effect of beaver dams on the hydrology of mountain streams: Example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium. *Journal of Hydrology*, 402(1-2), 92-102.

Pollock, M.M., Heim, M., & Werner, D. (2003). Hydrologic and geomorphic effects of beaver dams and their influence on fishes. In The Ecology and Management of Wood in World Rivers, Gregory, S.V., Boyer, K., & Gurnell, A. (eds). *American Fisheries Society*, 213–233.

Pollock, M.M., Pess, G.R., Beechie, T.J., & Montgomery, D. (2004). The importance of Beaver Ponds to Coho Salmon Production in the Stillaguamish River Basin, Washington, USA. *North American Journal of Fisheries Mangement*, 24(3), 749-760. DOI: 10.1577/M03-156.1

Schlosser, I.J. (1995). Dispersal, boundary processes, and trophic-level interactions in streams adjacent to beaver ponds. *Ecology*, 76(3), 908-925.

Stockholm Environment Institute (SEI). (2013) *Water Evaluation and Planning system* (Version 3.43) [Computer program]. Available at: http://www.weap21.org/index.asp?action=218 (Accessed 26 April 2013)

Snodgrass, J.W. & Meffe, G.W. (1998). Influence of beaver on stream fish assemblages: effects of pond age and watershed position. *Ecology*, 79(3), 928-942.

Tague, C.L. & Band, L.E. (2004). RHESSys: Regional Hydro-Ecologic Simulation System – An object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions*, 8, 1-42.

Tague, C. & Grant, G.E. (2009). Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. *Water Resources Research,* 45.

US Department of Agriculture (USDA) (2010). Natural Resources Conservation Service. *Rapid Watershed Assessment: Jemez Watershed.* Publication.

US Environmental Protection Agency (USEPA) (2006). *Wadeable Streams Assessment: A Collaborative Survery of the Nation's Streams.* Office of Research and Development. December 2006. Available at: www.epa.gov/owow/streamsurvey.

US Forest Service (USFS) (2001). *East Fork Jemez River: Stream Inventory Report*. Publication. Ed. Sean Ferrell. Santa Fe National Forest: US Forest Service. Print.

US Forest Service (USFS) (2001). *Cow Creek Stream Inventory Report*. Publication. Santa Fe National Forest: US Forest Service. Print.

US Forest Service (USFS) (2002). *Pecos River Stream Inventory Report*. Publication. Santa Fe National Forest: US Forest Service, 2002. Print.

US Forest Service (USFS) (2002). *San Antonio Creek Stream Inventory Report*. Publication. Santa Fe National Forest: US Forest Service, 2002. Print.

US Forest Service (USFS) (2003). *Rio De Las Vacas Stream Inventory Report*. Publication. Ed. Sean Ferrell. Santa Fe National Forest: US Forest Service. Print.

US Forest Service (USFS) (2005). *Cañones Creek Stream Inventory Report*. Publication. Santa Fe National Forest: US Forest Service. Print.

US Forest Service (USFS) (2006). *Rio Grande Cutthroat Trout (Oncorhynchus clarkii virginalis): A Technical Conservation Assessment.* Prepared by: Victoria L. Pritchard and David E. Cowley, Department of Fishery and Wildlife Sciences, New Mexico State University.

US Fish and Wildlife Service (USFWS) (2002). Southwestern willow flycatcher recovery plan. US Fish and Wildlife Service, Albuquerque, NM.

US Fish and Wildlife Service (USFWS) (2011). US Fish and Wildlife Service Species Assesment and Listing Priority Assignment Form for *Zapus hudsonius luteus*. Region 2, 4 March 2011. Lead Contact: New Mexico ESFO, Eric Hein.

US Fish and Wildlife Service (USFWS) (2013). Endangered and Threatened Wldlife and Plants; Proposed Designation of Critical Habitat for the New Mexico Meadow Jumping Mouse. *Federal Register, 50 CFR Part 17*. Docket No. FWS-R2-ES-2013-0014, 4500030114, RIN 1018-AZ32.

Utah Division of Wildlife Resources (Utah DWR) and Beaver Advisory Committee. (2010). Utah Beaver Management Plan. *DWR Publication*, 9, 29.

Western Regional Climate Center (WRCC) (2013). *Cooperative Climatological Data Summaries*. Available at: http://www.wrcc.dri.edu/climatedata/climsum/

Wild C. (2011). Beaver as a climate change adaptation tool: concepts and priority sites in New Mexico. *Seventh Generation Institute*, Santa Fe, NM.