TO WHAT EXTENT MIGHT BEAVER DAM BUILDING BUFFER WATER STORAGE LOSSES ASSOCIATED WITH A DECLINING SNOWPACK?

by

Konrad Hafen

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Watershed Science

Approved:

Joseph Wheaton, Ph.D. Major Professor	Brett Roper, Ph.D. Committee Member
Philip Bailey, Ph.D. Committee Member	Mark R. McLellan, Ph.D. Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2017

ABSTRACT

To What Extent Might Beaver Dam Building Buffer Water Storage Losses Associated with a Declining Snowpack?

by

Konrad Hafen, Master of Science

Utah State University, 2017

Major Professor: Dr. Joseph Wheaton
Department: Watershed Sciences

Dam building activity by North American Beaver (*Castor canadensis*) alters the timing and delivery of stream water and facilitates groundwater infiltration, overall increasing natural water storage behind and adjacent to dams. At the stream reach scale, increased water storage often alters hydrologic regimes by attenuating annual, and storm-event hydrographs, and increasing base flows. In the montane west, the most important water storage reservoirs are not human-made dams, but mountain snowpack, which slowly releases water through a mix of runoff and infiltration. Given estimates of decreasing snowpack with warming temperatures, beaver dams could provide a conceptually similar function to snowpack by delaying the delivery of precipitation by increasing surface and groundwater storage, thus lengthening residence time as water travels downstream. However, lack of predictive methods for modeling storage increases associated with relatively small magnitude beaver ponds at large spatial scales has precluded further investigation of this hypothesis. I address this knowledge gap by supplementing existing empirical data regarding the height of beaver dams and implement these empirical height distributions to develop the Beaver Dam Surface Water Estimation Algorithm (Chapter 2), a predictive model estimating beaver pond water storage that can be applied spatially at large scales. I then apply this model to estimate potential surface water storage and parameterize a groundwater model to estimate resulting groundwater storage increases for the entire Bear River basin under four different beaver dam capacity scenarios (Chapter 3). Estimated water storage changes from beaver dams are presented in the context of expected reductions in average annual maximum snow water equivalent, and existing and proposed reservoir storage within the basin. While the water storage provided by beaver dams is only a small fraction of expected snow water equivalent loss, it is not insubstantial and may prove beneficial for ecosystems where human-made reservoirs are not available to regulate hydrologic regimes. These results also stress the importance of further research examining how the cumulative effects of dams may affect the timing of runoff under changing precipitation regimes.

(129 pages)

PUBLIC ABSTRACT

To What Extent Might Beaver Dam Building Buffer Water Storage Losses Associated with a Declining Snowpack?

Konrad Hafen

Dams built by North American Beaver create natural water storage and slow water as it moves through streams. In portions of streams with beaver dams, these effects have been observed to decrease the peak magnitude of floods and increase base flow during annual summer droughts. In the western United States changes to streamflow patterns have been observed in recent decades with large spring floods coming earlier in the year, causing annual summer droughts to start earlier and last longer. These changes are linked to decreasing snowpack which acts as the most significant natural water storage reservoir by holding onto precipitation for many weeks to months and slowly releasing the water as it melts.

Given that snowpack is decreasing with warming temperatures, beaver dams provide a conceptually similar function to snowpack by increasing the residence time of precipitation as it travels through a drainage. Given that beaver dams can occupy large portions of the drainage network, it is logical to look to what degree beaver dams could compete with losses from snowpack. There are two ways in which beaver dams could buffer losses. One is through providing additional temporary water storage in both ponds and increases in groundwater storage. The second is through altering the timing and delivery of water downstream by increasing the time it takes to move downstream. I consider the first mechanism in this thesis, though to consider the second mechanism one needs an understanding of the first.

I test the idea that the additional water storage from increasing the number of beaver dams in a watershed could compensate for decreases in snowpack by simulating the amount of water beaver dams could store under different scenarios of both snowpack loss and the number of beaver dams on the landscape. To do this I first collect observations of 500 beaver dams to quantify the distribution of beaver dam sizes, then use this distribution to develop a model that predicts water storage using dam location and dam size. Results from the model of surface water storage are then input to an existing groundwater model to estimate increases in groundwater storage. Overall, our estimates suggest that beaver dams could store 6.65 million m^3 (6,000 acre-feet) of water in the Bear River basin, a small fraction of water lost from snowpack (1043.83 million m^3, 845,000 acre feet), where watersheds with the highest beaver dam water storage capacity account for approximately 3% of estimated snow water equivalent loss. However, in many watersheds beaver dam storage may account for close to 100% of snow water equivalent loss in valley-bottoms. Though storage from beaver dams may be limited, it could have significant impacts where human-made reservoirs are not available to regulate water resources. Furthermore, these small amounts of water storage, while ecologically significant, may not result in measurable changes to water availability for downstream water users which could present legal implications for beaver-based restoration strategies.

Konrad Hafen

ACKNOWLEDGMENTS

This research was made possible by grants from the US Forest Service and the Utah State University Office of Research and Graduate Studies. The support of my advisor, Joe Wheaton, was instrumental in designing and carrying out this project and I am grateful for his commitment of time and patience. Additionally, data selflessly provided by Beth Neilson, Milada Majerova, and Carol Volk made model validation possible. Chris Tennant came through in a big way to help with snowpack analyses on short notice. As members of my supervisory committee Brett Roper and Philip Bailey provided insightful suggestions, ideas, and supervision. Data collection for this study would not have been possible without Matt Meier and Creed Stephens. Phil Gardener provided essential advice and critiques on groundwater modeling techniques. Carl Saunders, Pete McHugh, and Wally Macfarlane were always available to listen to my ideas and point me in the right direction. All the other members of the ET-AL FHC lab group were always willing to help in whatever ways they could. Most importantly, I owe a great deal to my wife who not only helped with data visualization but also cheerfully put up with me working too much, supported all of my work and decisions, and encouraged me when things were difficult. Thank you all.

Konrad Hafen

CONTENTS

ABSTRACT iii

PUBLIC ABSTRACT v

ACKNOWLEDGMENTS vii

LIST OF TABLES x

LIST OF FIGURES xii

CHAPTER

1. INTRODUCTION 1
    Background 1
    Water Storage in the Western United States 2
    Local Beaver Dam Impacts 4
    Beaver Dam Impacts at Broad Spatial Scales 6
    Objectives 8
    References 10

2. SPATIALLY MODELING SURFACE WATER STORAGE ASSOCIATED WITH BEAVER DAMS 16
    Abstract 16
    Introduction 17
    Methods 24
        Study Sites 24
        Data Collection 27
        Data Analysis 36
        The BD-SWEA Model 37
        BD-SWEA Validation 38
    Results 41
        Field Data 41
        High-resolution Topography 46
        BD-SWEA Validation 46
    Discussion 50
    References 55

3. TO WHAT DEGREE COULD BEAVER DAMS BUFFER A DECLINING SNOWPACK? 60
    Abstract 60
    Introduction 61
    Methods 67

        Study Area 67
        Modeling Beaver Pond Water Storage 71
        Projected Snowpack Decreases 77
    Results 80
        Beaver Dam Capacities 80
        Beaver Dam Water Storage 83
        Projected Snowpack Decreases 89
    Discussion 96
    References 104

4. SIGNIFICANCE 110
    References 115

LIST OF TABLES

Table Page

2.1. Summary of dam heights and dam lengths reported from studies examining multiple beaver dams constructed by North American beaver (*Castor canadensis*). 23

2.2. Summary of data collection sites and the type(s) of data collected, or available, for each site (Figure 2.1). 26

2.3. Variables collected during rapid beaver dam surveys, and value options for each variable. 29

2.4. Definitions of morphometric measurements extracted from high-resolution digital elevation models (DEMs) and water surface elevation (WSE) rasters of beaver ponds. 33

2.5. Summary of the total number of dams for which rapid field assessments were conducted by 12 digit hydrologic unit (HU12). 42

2.6. Summary of dam heights, crest lengths, pond areas, and pond volumes extracted from high-resolution topographic surveys of beaver dams and ponds, where n equals the number of observations for each variable, and SD the standard deviation. 46

2.7. Mean and standard deviation values for observed (Obs.) and modeled (Mod.) areas and volumes of beaver ponds. 49

3.1. Length of perennial streams for each HU8, maximum estimated dam capacity, and percent of the landscape occupied by valley-bottoms (VB) of perennial streams. 81

3.2. Estimated water storage for each dam capacity scenario with low, median, and high estimates of dam height. 86

3.3. The number of modeled primary and secondary beaver dams, total length of perennial stream (Stream Length), modeled dam density, total change in water storage (TS), change in surface water storage (SWS), and change in groundwater storage (GWS) at median dam height for each HU8 under each BRAT dam capacity scenario. 87

3.4. Mean and standard deviation (SD) values of potential increases to surface water (SW) and groundwater (GW) for individual beaver dams. 89

3.5. Estimated volumetric loss in SWE for each HU8 under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C. 92

LIST OF FIGURES

Figure Page

1.1. Theoretical annual hydrographs depicting the hypothesized effects of beaver dams on the timing of stream runoff. 9

2.1. Utah, Idaho, and Oregon HU12s where topographic or field data were collected, with an inset of the Little Bear – Logan River HU8 showing locations of dams identified from aerial imagery. 27

2.2. Examples of dam complex delineation for dam complexes where (A) complex boundaries are relatively discrete, (B) complex boundaries are somewhat arbitrary, and (C) complexes do not contain primary dams. 31

2.3. Measurements taken in the field and derived from high resolution topography. 34

2.4. Example of (A) manually digitized beaver dam and beaver pond input features of maximum plausible inundation extent (roughly digitized), beaver dam crest, and a region reflecting the base of the beaver dam. 35

2.5. The Beaver Dam Surface Water Estimation Algorithm (BD-SWEA) for modeling inundation extent and water depth of a pond created by a dam 3.5 units tall, the dam's elevation above sea level is 24.5 units...........39

2.6. Dam height distributions of intact beaver dams for all dams, primary dams, and secondary dams. 43

2.7. Dam height by dam type, primary construction material, and HU12 watershed. 44

2.8. Number of dams per dam complex including all dams, intact dams, and damaged dams where damaged dams are the combination of breached and blown-out dams. 45

2.9. Linear regression validation (D, E, F) of BD-SWEA pond area estimates modeled with 1 m (A, D) and 10 m (B, C, E, F) DEM inputs, and comparison of distributions of modeled and measured pond areas (A, B, C). 48

2.10. Linear regression validation and distributions of measured pond volumes and pond volumes modeled with BD-SWEA using 1 m (A, C) and 10 m (B, D) DEM inputs. 49

2.11. Dam locations and extents for data collected in the field with an iPad and GPS (A), modeled pond extents and depths using BD-SWEA with a 1 m LiDAR DEM input (B), and modeled pond extents and depths using BD-SWEA with a 10 m NED DEM input (C), for a stream reach in the Temple Fork HU12. 54

3.1. Theoretical illustration of the extent to which beaver may increase surface water and groundwater storage. 66

3.2. The National Hydrography Dataset perennial stream network, existing major reservoirs, locations of proposed reservoirs, and 8 digit hydrologic units (HU8) for the Bear River basin. 69

3.3. (A)Violin plots of contrasting elevation distributions (i.e. hypsometry) for 8 digit hydrologic units (HU8) in the Bear River basin with white circles showing the median elevation of each distribution. 70

3.4. (A) Initial boundary conditions for head elevation, (B) head elevations to represent beaver ponds, (C) and the difference between initial head values and beaver pond head values. 78

3.5. Groundwater well locations at the Bridge Creek and Curtis Creek Study sites. 79

3.6. Maximum estimated beaver dam capacity for the Bear River basin. 82

3.7. Spatial distribution of the primary and secondary beaver dams for which volume was modeled with BD-SWEA and MODFLOW at (A) 5%, (B) 25%, (C) 50%, and (D) quasi 100% of maximum dam capacity estimated by BRAT. 83

3.8. Linear regression validation of groundwater changes estimated with MODFLOW against groundwater elevation changes measured at wells via depth-sounder at (A) Curtis Creek, UT and pressure transducer at (B) Bridge Creek, OR. 85

3.9. Estimates of water storage provided by beaver dams modeled at 5%, 25%, 50%, and quasi 100% of maximum dam capacity for 0.025, 0.5, and 0.975 dam height quantiles. 88

3.10. The number of beaver dams modeled and the potential change in water storage resulting from beaver dam construction for each HU12 in the Bear River basin under dam capacity scenarios of 5%, 25%, 50%, and quasi 100%. 90

3.11. Richard’s equation fit to the Upper Bear HU8, and all other HU8s in the Bear River basin........91

3.12. Volumetric SWE loss and percent of SWE loss that could mitigated by beaver dams of median dam height at quasi 100% of maximum dam capacity under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C for each HU12 in the Bear River basin........93

3.13. Volumetric SWE loss from valley-bottoms and percent of valley-bottom SWE loss that could be mitigated by beaver dams of median dam height at quasi 100% of maximum dam capacity under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C for each HU12 in the Bear River basin........94

3.14. Existing reservoir storage, proposed increases to reservoir storage, maximum estimated storage from beaver dams of median height at quasi 100% of maximum estimated capacity, and estimated volumetric loss in mean maximum SWE under 1 ˚C and 4 ˚C warming scenarios by elevation........95

3.15. Total volume of water stored in existing reservoirs, potential storage from proposed reservoirs, and expected storage loss from snowpack under warming scenarios of 1 ˚C and 4 ˚C compared to the total storage beaver dams may provide with median dam heights at quasi 100% of maximum estimated capacity........96

3.16. Maximum degree to which increased water storage from beaver dam construction may increase baseflow over a 30 day period. 103

CHAPTER 1

INTRODUCTION

Background

Most streams in mountainous regions of the western United States are characterized by a spring snowmelt flood, which delivers up to 80% of the annual water runoff, followed by an annual summer low flow period (Stewart *et al.*, 2004). During the past 50 years, earlier peak runoff dates for many streams have lengthened the duration of annual summer low flow (Luce and Holden, 2009; Stewart *et al.*, 2004, 2005). Both the ecosystems adapted to these snow-melt dominated flow regimes, and the water resources management infrastructure designed and operated to capture a portion of that water for 'beneficial uses' will need to adapt to the new realities of a changing flow regime. In part, this may entail looking for additional water storage to offset the losses in snowpack, buffer decreased summer water availability and meet consumption demands (Barnett *et al.*, 2005). Snowpack declines and shifts to rain-dominated or rain-snow mix precipitation regimes (Huss *et al.*, 2017; Klos *et al.*, 2014) are projected to continue for the western United States, increasing variability in the quantity and timing of stream runoff (Hamlet *et al.*, 2005; Mote, 2006; Mote *et al.*, 2005). Future uncertainty in streamflow will likely increase the difficulty of meeting anticipated consumptive water demand and ecological needs (Christensen *et al.*, 2004; Elsner *et al.*, 2010; Milly *et al.*, 2005; Seager *et al.*, 2013; Stewart *et al.*, 2005). Most regions of the western United States already have high populations with respect to available water resources, and when projected population increases in western states over the next 50 years (Colby and Ortman, 2015) are coupled with modeled climate change effects, additional stress is expected on water resources in this region (Roy *et al.*, 2012; Tidwell *et al.*, 2014; Törnblom *et al.*, 2000).

Water Storage in the Western United States

Perhaps of greater concern than population increases, are estimated decreases in snowpack as temperatures increase in the western US (Huss *et al.*, 2017; Klos *et al.*, 2014; Mote *et al.*, 2005). In montane regions, accumulation of frozen precipitation throughout the winter months provides a substantial, temporary reservoir of water which is slowly released during spring and early summer as temperatures warm. The simple process of storing water in a solid phase on the land-surface can sequester vast quantities of water and delay the delivery of that water by weeks to months. Depending on physiographic setting and weather patterns, snowpack runoff in streams of the western US generally reaches its peak between early April and late June, with above average flows often continuing into August and September. This delay in water delivery shifts water availability from the time when precipitation falls in winter months to late spring, summer, and early autumn when water demand is greatest. Human-made water storage reservoirs take advantage of seasonal streamflow patterns by storing snowpack runoff during annual spring floods and releasing stored water during annual low flow periods of late summer and autumn, further extending water availability when water supply is lowest and buffering hydrologic variability. Warming temperatures decrease not only the size of the snowpack reservoir but also the duration of water storage. Less snow and earlier runoff places additional stress on human-made water storage reservoirs as supplies must provide water for extended periods of time, requiring more storage capacity or implementation of other methods to increase the residence time of water as it moves downstream (Barnett *et al.*, 2005).

Some states are actively seeking to mitigate future change and uncertainty in hydrologic regimes and consumptive demands through construction of water storage reservoirs to buffer variability in the timing and quantity of snowmelt runoff (Ruple, 2012). While such projects may create jobs, recreational opportunities, and provide some stability for increasingly variable hydrologic regimes (Bowen Collins & Associates and HDR Engineering, 2014; Ruple, 2012), anticipated ecological and hydrological consequences may outweigh benefits in regions where water resources have already been widely developed (Graf, 1999; Ligon *et al.*, 1995; Nilsson and Berggren, 2000; Wurtsbaugh *et al.*, 2016). Moreover, the cost of modern reservoir projects relative to their modest increases in storage capacity have been difficult to justify to taxpayers since the late 1970s (George *et al.*, 2016; Graf, 1999; Ho *et al.*, 2017; Lindström and Grani, 2012). In regions of the western United States, reservoir capacity is already greater than the average volume of annual flow (Graf, 1999), and changes to stream habitat, riparian vegetation, and flow and temperature regimes resulting from construction of large dams are of ecological concern. Construction of additional water storage dams may provide little added hydrologic stability with great ecological cost (Ligon *et al.*, 1995; Nilsson and Berggren, 2000). In northern Utah, Wurtsbaugh et al. (2016) warn that further diversion from rivers draining to the Great Salt Lake may facilitate drying of the lake which provides a host of economic, ecologic, and hydrologic services. With current pressure to remove dams for ecological restoration (Null *et al.*, 2014; O'Connor *et al.*, 2015) creative, ecologically sustainable methods for increasing water storage are needed to address future variability and uncertainty of hydrologic regimes (Ho *et al.*, 2017; Palmer *et al.*, 2014).

Local Beaver Dam Impacts

In contrast to expected decreases in snowpack and earlier spring runoff, dams built by North American Beaver (*Castor canadensis*) can provide temporary surface water and groundwater storage (Nyssen *et al.*, 2011; Puttock *et al.*, 2017; Westbrook *et al.*, 2006). Locally, this added water storage may attenuate floods, increase base flows (Majerova *et al.*, 2015; Nyssen *et al.*, 2011), and facilitate groundwater recharge (Bouwes *et al.*, 2016; Feiner and Lowry, 2015; Westbrook *et al.*, 2006). These hydrologic impacts also benefit many other aquatic and terrestrial species (Rosell *et al.*, 2005; Wright *et al.*, 2002), provide biogeochemical benefits (Correll *et al.*, 2000; Naiman *et al.*, 1994; Wohl, 2013), and establish desirable physical stream form (Pollock *et al.*, 2014; Wohl, 2011). The ability of beaver to alter aquatic and riparian ecosystems (Burchsted *et al.*, 2010; Hood and Larson, 2015; Naiman *et al.*, 1988; Rosell *et al.*, 2005) has prompted beaver-assisted restoration efforts (through direct beaver relocation or construction of beaver dam like structures) which have successfully addressed physical and biotic condition objectives (Bouwes *et al.*, 2016; Curran and Cannatelli, 2014; Pollock *et al.*, 2015, 1995, 2014; Runyon *et al.*, 2014). In many instances, beaver reintroduction, or increasing the number of beaver dams throughout riverscapes, may be a viable restoration method as heavy extirpation of beaver prior to the 19th century has left their populations at only a small fraction of historical abundance (Dolan, 2010). Macfarlane et al. (2014) estimate that in Utah beaver dams may occur at only 8% of maximum capacity with capacity in some watersheds as low as 1% of the maximum, leaving ample resources and opportunity for construction of many more beaver dams.

From a hydrologic perspective, increased water storage and hydrograph attenuation resulting from construction of individual beaver dams and beaver dam complexes suggests beaver dams may provide desirable effects for downstream water users (Beedle, 1991; Hill and Duval, 2009; Hood and Bayley, 2008; Johnston and Naiman, 1990a; Lowry, 1993). Beaver dams directly impound water and increase the areal coverage of water across landscapes where intermittent or perennial water sources are available (Hood and Bayley, 2008; Johnston and Naiman, 1990a). In the mountainous regions of the western US, the effects of beaver dams are generally limited to the valley-bottoms of perennial (and occasionally intermittent) streams which comprise approximately 2-10% of the landscape (Gilbert *et al.*, 2016; Macfarlane *et al.*, 2017). Beaver dams change stream hydraulics by increasing the overall roughness of the stream, generally resulting in slower water velocities and increased water depths resulting from increased water surface elevations created by beaver dams (Bouwes *et al.*, 2016; Stout *et al.*, 2016; Westbrook *et al.*, 2006). Slower stream velocities and increased water surface elevations facilitate groundwater recharge and increase the volume of potential groundwater storage (Feiner and Lowry, 2015; Hill and Duval, 2009; Lowry, 1993; Westbrook *et al.*, 2006). Evapotranspiration losses may be increased with more surficial exposure of open water and as raised groundwater tables make additional water available to plants (Burchsted *et al.*, 2010; Burns and McDonnell, 1998; Woo and Waddington, 1990). Similar to beaver dams, small earthen dams and water spreaders, used primarily for flood control, may attenuate peak flows and extend spring runoff further into the year, even facilitating transformation of some streams from intermittent to perennial without the massive ecological consequence of large structures (Frickel, 1972; Kennon, 1966).

Beaver Dam Impacts at Broad Spatial Scales

At the scale of individual beaver dams and dam complexes, there is strong support for the ability of beaver dams to alter local hydrographs by attenuating peak flows and increasing base flows during periods with reduced precipitation and/or runoff (Burns and McDonnell, 1998; Nyssen *et al.*, 2011; Puttock *et al.*, 2015; Stout *et al.*, 2016; Woo and Waddington, 1990). Hydrograph alterations are driven by increasing residence time of water through temporary surface and groundwater storage created by beaver dams. Some empirical relationships have been developed to estimate the volume of water which beaver dams of a given height and width may impound (Beedle, 1991; Karran *et al.*, 2016; Klimenko and Eponchintseva, 2015). However, how the local hydrologic impacts of beaver dams combine and culminate at broader landscape scales, and whether these impacts will be detectable or meaningful on larger mainstem rivers remains unknown and falls in the realm of hopeful conjecture and speculation at this point (e.g. Majerova et al., 2015; Nyssen et al., 2011). What important studies on hydrologic impacts do exist, suffer from small sample sizes and do not adequately account for different hydrologic signatures across different physiographic and climatic regions. Simple, but useful, empirical measurements and relationships between the morphometries of beaver dams (e.g. dam height, dam width) and resulting water storage volumes need further exploration. Additionally, increases in groundwater tables facilitated by the pond may provide more water storage in partly-confined and laterally unconfined valley settings (cf. Fryirs et al., 2016) than the actual impounded water (Feiner and Lowry, 2015; Lowry, 1993). Therefore, empirical data encompassing additional watersheds and estimating groundwater storage, or a spatially explicit modeling approach, are needed to adequately estimate water storage at larger scales. However, the boundary conditions necessary to model such impacts require information on the spatial configuration of beaver dams throughout a drainage network, as well as how much additional surface water storage and groundwater storage is possible with realistic numbers and distributions of beaver dams. Without a quantitative understanding of the magnitude to which beaver dams and dam complexes store water it is difficult to determine the extent to which hydrology may be altered at watershed scales. Yet, with growing implementation of beaver relocation and construction of beaver-mimicking structures for restoration purposes, water and land managers desperately need research and the ability to evaluate the hydrologic impacts of beaver dams on the timing and delivery of water.

Until recently, watershed-scale modeling of potential beaver impacts has been precluded by a limited understanding of how many beaver dams stream reaches could support (Macfarlane *et al.*, 2017). Since beaver populations have not yet recovered from heavy extirpation during the extensive fur trade of the 17th-19th centuries (Dolan, 2010; Kramer *et al.*, 2012), their historic prevalence and pre-extirpation impacts on landscape and hydrologic conditions are uncertain (Polvi and Wohl, 2012; Wohl, 2005, 2011). Even with such knowledge, in a modern water management context, it is more important to understand what is possible in today’s landscapes, given modern climate, land use, and manipulation of water resources. This knowledge gap has now been partially filled by a recent development of spatially-explicit estimates of the maximum beaver dam density which may be supported throughout entire drainage networks by Macfarlane et al. (2017).

Such dam capacity estimates are a critical link to modeling realistic upper limits of the hydrologic effects of beaver dams in comparison to current dam densities and exploring current and potential effects of beaver dams on water resources across entire drainage networks, and indicate that the majority of watersheds have great potential to support many more beaver dams (Macfarlane *et al.*, 2014).

Objectives

Results of small-scale hydrologic studies and the potential for riverscapes to support greater dam capacities suggest the cumulative hydrologic impacts of beaver dams may be meaningful at a water management level. However, the potential hydrologic impacts of beaver dams have not yet been assessed at such a scale, and relationships between beaver dam storage capacity, the existing storage capacity of human-made reservoirs, and expected changes in precipitation have not been quantified. My objectives are to (1) develop a methodology to predictively estimate surface water storage created by beaver dams, (2) estimate changes in groundwater storage facilitated by beaver dam construction, and (3) estimate the total water storage that may be provided under four different scenarios of increased beaver dam construction for the Bear River Basin, and contextualize the quantity of this storage with existing storage from human-made reservoirs and projected losses in snow water equivalent. Objective 1 is addressed in Chapter 2, herein, and objectives 2 and 3 are addressed in Chapter 3. This research provides a first assessment of the degree to which beaver may alter hydrology at broader spatial scales meaningful to water resources management. Moreover, I present methods and open source tools for spatially assessing the impact of beaver dams on surface water and groundwater, making the extension of these analyses to other watersheds tractable for other researchers and land managers. While I do not explicitly address the impacts of increased beaver dam construction on the timing of water delivery, these results provide data and means to parameterize and validate hydrologic modeling efforts which can provide more insight on how beaver dams affect hydrologic dynamics.

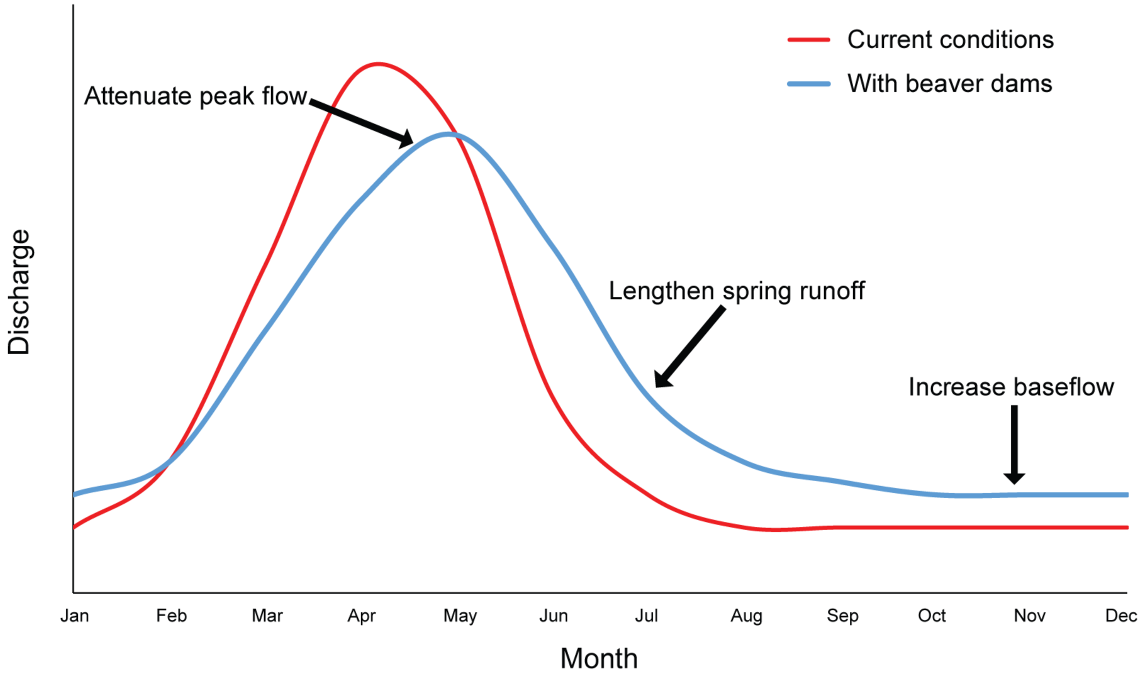


Figure 1.1. Theoretical annual hydrographs depicting the hypothesized effects of beaver dams on the timing of stream runoff.

REFERENCES

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier, 2005. Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions. Nature 438:303–309, doi: 10.1038/nature04141.

Beedle, D.L., 1991. Physical Dimensions and Hydrologic Effects of Beaver Ponds on Kuiu Island in Southeast Alaska., http://ir.library.oregonstate.edu/xmlui/handle/1957/9343, *accessed* 1 Feb 2016.

Bouwes, N., N. Weber, C.E. Jordan, W.C. Saunders, I.A. Tattam, C. Volk, J.M. Wheaton, and M.M. Pollock, 2016. Ecosystem Experiment Reveals Benefits of Natural and Simulated Beaver Dams to a Threatened Population of Steelhead (Oncorhynchus Mykiss). Scientific Reports 6:28581, doi: 10.1038/srep28581.

Bowen Collins & Associates and HDR Engineering, 2014. Bear River Pipeline Concept Report., https://www.cachecounty.org/assets/department/water/brpipeline/Vol 1_Final_Bear River Pipeline Concept Rpt.pdf, *accessed* 5 Apr 2017.

Burchsted, D., M. Daniels, R. Thorson, and J. Vokoun, 2010. The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters. BioScience 60:908–922, doi: 10.1525/bio.2010.60.11.7.

Burns, D. a. and J.J. McDonnell, 1998. Effects of a Beaver Pond on Runoff Processes: Comparison of Two Headwater Catchments. Journal of Hydrology 205:248–264, doi: 10.1016/S0022-1694(98)00081-X.

Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier, and R.N. Palmer, 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climate Change 62:337–363, doi: 10.1023/B:CLIM.0000013684.13621.1f.

Colby, S.L. and J.M. Ortman, 2015. Projections of the Size and Composition of the US Population: 2014 to 2060. US Census Bureau, Ed:25–1143.

Correll, D.L., T.E. Jordan, and D.E. Weller, 2000. Beaver Pond Biogeochemical Effects in the Maryland Coastal Plain. Biogeochemistry 49:217–239, doi: 10.1023/A:1006330501887.

Curran, J.C. and K.M. Cannatelli, 2014. The Impact of Beaver Dams on the Morphology of a River in the Eastern United States with Implications for River Restoration. Earth Surface Processes and Landforms 39:1236–1244, doi: 10.1002/esp.3576.

Dolan, E.J., 2010. Fur, Fortune, and Empire: The Epic History of the Fur Trade in Ameria. W. W. Norton & Company, New York, New York.

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J. a. Vano, K.E.B. Mickelson, S.Y. Lee, and D.P. Lettenmaier, 2010. Implications of 21st Century Climate Change for the Hydrology of Washington State. Climatic Change 102:225–260, doi: 10.1007/s10584-010-9855-0.

Feiner, K. and C.S. Lowry, 2015. Simulating the Effects of a Beaver Dam on Regional Groundwater Flow through a Wetland. Journal of Hydrology: Regional Studies 4:675–685.

Frickel, D.G., 1972. Hydrology and Effects of Conservation Structures, Willow Creek Basin, Valley County, Montana, 1954-68.

Fryirs, K.A., J.M. Wheaton, and G.J. Brierley, 2016. An Approach for Measuring Confinement and Assessing the Influence of Valley Setting on River Forms and Processes. Earth Surface Processes and Landforms.

George, M.W., R.H. Hotchkiss, and R. Huffaker, 2016. Reservoir Sustainability and Sediment Management. Journal of Water Resources Planning and Management:4016077.

Gilbert, J.T., W.W. Macfarlane, and J.M. Wheaton, 2016. TheValley Bottom Extraction Tool (V-BET): A GIS Tool for Delineating Valley Bottoms across Entire Drainage Networks. Computers & Geosciences.

Graf, W.L., 1999. Dam Nation: A Geographic Census of American Dams and Their Large-Scale Hydrologic Impacts. Water Resources Research 35:1305–1311.

Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier, 2005. Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States. Journal of Climate 18:4545–4561, doi: 10.1175/JCLI3538.1.

Hill, A.R. and T.P. Duval, 2009. Beaver Dams along an Agricultural Stream in Southern Ontario, Canada: Their Impact on Riparian Zone Hydrology and Nitrogen Chemistry. Hydrological Processes 23:1324–1336, doi: 10.1002/hyp.7249.

Ho, M., U. Lall, M. Allaire, N. Devineni, H.H. Kwon, I. Pal, D. Raff, and D. Wegner, 2017. The Future Role of Dams in the United States of America. Water Resources Research.

Hood, G.A. and S.E. Bayley, 2008. Beaver (Castor Canadensis) Mitigate the Effects of Climate on the Area of Open Water in Boreal Wetlands in Western Canada. Biological Conservation 141:556–567, doi: 10.1016/j.biocon.2007.12.003.

Hood, G.A. and D.G. Larson, 2015. Ecological Engineering and Aquatic Connectivity: A New Perspective from Beaver-Modified Wetlands. Freshwater Biology 60:198–208, doi: 10.1111/fwb.12487.

Huss, M., B. Bookhagen, C. Huggel, D. Jacobsen, R. Bradley, J. Clague, M. Vuille, W. Buytaert, D. Cayan, G. Greenwood, B. Mark, A. Milner, R. Weingartner, and M. Winder, 2017. Towards Mountains without Permanent Snow and Ice. Earth's Future:n/a-n/a, doi: 10.1002/2016EF000514.

Johnston, C.A. and R.J. Naiman, 1990. The Use of a Geographic Information System to Analyze Long-Term Landscape Alteration by Beaver. Landscape Ecology 4:5–19.

Karran, D.J., C.J. Westbrook, J.M. Wheaton, C.A. Johnston, and A. Bedard-Haughn, 2016. Rapid Surface Water Volume Estimations in Beaver Ponds. Hydrology and Earth System Sciences Discussions, doi: 10.5194/hess-2016-352.

Kennon, F.W., 1966. Hydrologic Effects of Small Reservoirs in Sandstone Creek Watershed, Beckham and Roger Mills Counties, Western Oklahoma.

Klimenko, D.E. and D.N. Eponchintseva, 2015. Experimental Hydrological Studies of Processes of Failure of Beaver Dams and Pond Draining. Biology Bulletin 42:882–890.

Klos, P.Z., T.E. Link, and J.T. Abatzoglou, 2014. Extent of the Rain-Snow Transition Zone in the Western U.S. under Historic and Projected Climate. Geophysical Research Letters:n/a-n/a, doi: 10.1002/2014GL060500.

Kramer, N., E.E. Wohl, and D.L. Harry, 2012. Using Ground Penetrating Radar to "unearth" Buried Beaver Dams. Geology 40:43–46.

Ligon, F.K., W.E. Dietrich, and W.J. Trush, 1995. Downstream Ecological Effects of Dams. BioScience 45:183–192.

Lindström, A. and J. Grani, 2012. Large-Scale Water Storage in the Water, Energy and Food Nexus: Perspectives on Benefits, Risks and Best Practices. Stockholm International Water Institute.

Lowry, M.M., 1993. Groundwater Elevations and Temperature Adjacent to a Beaver Pond in Central Oregon. Oregon State University, http://ir.library.oregonstate.edu/jspui/handle/1957/9566, *accessed* 18 Dec 2013.

Luce, C.H. and Z.A. Holden, 2009. Declining Annual Streamflow Distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters 36.

Macfarlane, W.W., J.M. Wheaton, N. Bouwes, M.L. Jensen, J.T. Gilbert, N. Hough-Snee, and J.A. Shivik, 2017. Modeling the Capacity of Riverscapes to Support Beaver Dams. Geomorphology 277:72–99.

Macfarlane, W.W., J.M. Wheaton, and M.L. Jensen, 2014. The Utah Beaver Restoration Assessment Tool : A Decision Support & Planning Tool.

Majerova, M., B.T. Neilson, N.M. Schmadel, J.M. Wheaton, and C.J. Snow, 2015. Impacts of Beaver Dams on Hydrologic and Temperature Regimes in a Mountain Stream. Hydrology and Earth System Sciences 19:3541–3556, doi: 10.5194/hess-19-3541-2015.

Milly, P.C.D., K.A. Dunne, and A. V Vecchia, 2005. Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate. Nature 438:347–350.

Mote, P.W., 2006. Climate-Driven Variability and Trends in Mountain Snowpack in Western North America. Journal of Climate 19:6209–6220, doi: 10.1175/JCLI3971.1.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier, 2005. Declining Mountain Snowpack in Western North America. Bulletin of the American Meteorological Society 86:39–49, doi: 10.1175/BAMS-86-1-39.

Naiman, R.J., C.A. Johnston, and J.C. Kelley, 1988. Alteration of North American Streams by Beaver. Bioscience 38:753–762, http://www.jstor.org/stable/pdfplus/1310784.pdf?acceptTC=true&acceptTC=true&jpdConfirm=true, *accessed* 18 Dec 2013.

Naiman, R.J., G. Pinay, C.A. Johnston, and J. Pastor, 1994. Beaver Influences on the Long-Term Biogeochemical Characteristics of Boreal Forest Drainage Networks. Ecology:905–921, http://www.jstor.org/stable/1939415, *accessed* 2 Mar 2014.

Nilsson, C. and K. Berggren, 2000. Alterations of Riparian Ecosystems Caused by River Regulation. BioScience 50:783–792.

Null, S.E., J. Medellín-Azuara, A. Escriva-Bou, M. Lent, and J.R. Lund, 2014. Optimizing the Dammed: Water Supply Losses and Fish Habitat Gains from Dam Removal in California. Journal of Environmental Management 136:121–131.

Nyssen, J., J. Pontzeele, and P. Billi, 2011. Effect of Beaver Dams on the Hydrology of Small Mountain Streams: Example from the Chevral in the Ourthe Orientale Basin, Ardennes, Belgium. Journal of Hydrology 402:92–102, doi: 10.1016/j.jhydrol.2011.03.008.

O’Connor, J.E., J.J. Duda, and G.E. Grant, 2015. 1000 Dams down and Counting. Science 348:496–497.

Palmer, M.A., S. Filoso, and R.M. Fanelli, 2014. From Ecosystems to Ecosystem Services: Stream Restoration as Ecological Engineering. Ecological Engineering 65:62–70.

Pollock, M.M., T.J. Beechie, J.M. Wheaton, C.E. Jordan, N. Bouwes, N. Weber, and C. Volk, 2014. Using Beaver Dams to Restore Incised Stream Ecosystems. BioScience 64:279–290, doi: 10.1093/biosci/biu036.

Pollock, M.M., G. Lewallen, K. Woodruff, C.E. Jordan, and J.M. Castro, 2015. The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains.

Pollock, M.M., R.J. Naiman, H.E. Erickson, C.A. Johnston, J. Pastor, and G. Pinay, 1995. Beaver as Engineers: Influences on Biotic and Abiotic Characteristics of Drainage Basins. Linking Species & Ecosystems. Springer, pp. 117–126, http://link.springer.com/chapter/10.1007/978-1-4615-1773-3_12, *accessed* 28 Feb 2014.

Polvi, L.E. and E. Wohl, 2012. The Beaver Meadow Complex Revisited–the Role of Beavers in Post-glacial Floodplain Development. Earth Surface Processes and Landforms 37:332–346.

Puttock, A., A.M. Cunliffe, K. Anderson, and R.E. Brazier, 2015. Aerial Photography Collected with a Multirotor Drone Reveals Impact of Eurasian Beaver Reintroduction on Ecosystem Structure. Journal of Unmanned Vehicle Systems.

Puttock, A., H.A. Graham, A.M. Cunliffe, M. Elliott, and R.E. Brazier, 2017. Eurasian Beaver Activity Increases Water Storage, Attenuates Flow and Mitigates Diffuse Pollution from Intensively-Managed Grasslands. Science of The Total Environment 576:430–443.

Rosell, F., O. Bozsér, P. Collen, and H. Parker, 2005. Ecological Impact of Beavers Castor Fiber and Castor Canadensis and Their Ability to Modify Ecosystems. Mammal Review 35:248–276, doi: 10.1111/j.1365-2907.2005.00067.x.

Roy, S.B., L. Chen, E.H. Girvetz, E.P. Maurer, W.B. Mills, and T.M. Grieb, 2012. Projecting Water Withdrawal and Supply for Future Decades in the US under Climate Change Scenarios. Environmental Science & Technology 46:2545–2556.

Runyon, M.J., D.B. Tyers, B.F. Sowell, and C.N. Gower, 2014. Aspen Restoration Using Beaver on the Northern Yellowstone Winter Range under Reduced Ungulate Herbivory. Restoration Ecology 22:555–561.

Ruple, J.C., 2012. Water for Power in the Twenty-First Century: What a Growing Population, Changing Climate, and Energy Development Mean for Utah’s Water Resources. Utah Envtl. L. Rev. 32:363.

Seager, R., M. Ting, C. Li, N. Naik, B. Cook, J. Nakamura, and H. Liu, 2013. Projections of Declining Surface-Water Availability for the Southwestern United States. Nature Climate Change 3:482–486.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2004. Changes in Snowmelt Runoff Timing in Western North America Under a “Business As Usual” Climate Change Scenario. Climatic Change 62:217–232.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate 18:1136–1155, doi: 10.1175/JCLI3321.1.

Stout, T.L., M. Majerova, and B.T. Neilson, 2016. Impacts of Beaver Dams on Channel Hydraulics and Substrate Characteristics in a Mountain Stream. Ecohydrology.

Tidwell, V.C., B.D. Moreland, K.M. Zemlick, B.L. Roberts, H.D. Passell, D. Jensen, C. Forsgren, G. Sehlke, M.A. Cook, and C.W. King, 2014. Mapping Water Availability, Projected Use and Cost in the Western United States. Environmental Research Letters 9:64009.

Törnblom, J., P. Anglestam, G. Hartman, L. Henrikson, and G. Slöberg, 2000. Toward a Research Agenda for Water Policy Implementation : Knowledge about Beaver (Castor Fiber) as a Tool for Water Management with a Catchment Perspective. Baltic Forestry 17:154–161.

Westbrook, C.J., D.J. Cooper, and B.W. Baker, 2006. Beaver Dams and Overbank Floods Influence Groundwater-Surface Water Interactions of a Rocky Mountain Riparian Area. Water Resources Research 42:1–12, doi: 10.1029/2005WR004560.

Wohl, E., 2005. Compromised Rivers: Understanding Historical Human Impacts on Rivers in the Context of Restoration. Ecology and Society 10:2.

Wohl, E., 2011. What Should These Rivers Look like? Historical Range of Variability and Human Impacts in the Colorado Front Range, USA. Earth Surface Processes and Landforms 36:1378–1390.

Wohl, E., 2013. Landscape-scale Carbon Storage Associated with Beaver Dams. Geophysical Research Letters 40:3631–3636.

Woo, M.-K. and J.M. Waddington, 1990. Effects of Beaver Dams on Subarctic Wetland Hydrology. Arctic 43:223–230, doi: 10.14430/arctic1615.

Wright, J., C. Jones, and A. Flecker, 2002. An Ecosystem Engineer, the Beaver, Increases Species Richness at the Landscape Scale. Oecologia 132:96–101, doi: 10.1007/s00442-002-0929-1.

Wurtsbaugh, W., C. Miller, S. Null, P. Wilcock, M. Hahnenberger, and F. Howe, 2016. Impacts of Water Development on Great Salt Lake and the Wasatch Front.

CHAPTER 2

SPATIALLY MODELING SURFACE WATER STORAGE ASSOCIATED WITH BEAVER DAMS

ABSTRACT

Ecological and physical aspects of riparian ecosystems can be dramatically altered by dam building activities of North American Beaver (*Castor canadensis*). The extent to which beaver's ecosystem engineering alters these riverscapes is driven by the frequency, density, and size of the dams constructed. The impacts of an individual dam are dependent primarily upon its height and length, which drive the inundation extent and water depths of the resulting pond. While the impacts of beaver dams on the surrounding environment and methods for quantifying the impacts of dams have been conceptualized and quantified, few methods or data exist to predictively identify the potential impacts of beaver dams. Furthermore, functional differences between dam types built by beaver may result in different dam sizes which drive different impacts. We collect basic characteristics for over 1700 beaver dams and use these data to parameterize, calibrate, and validate the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA), a spatially-explicit model, to estimate the extent and depth of water impounded by beaver dams. Additionally, we use these data to differentiate between the sizes of different dam types and quantify their relative frequency. On average, primary dams were 0.46 m taller than secondary dams, and occurred at lower frequencies with 15% of dams being primary and the rest secondary. BD-SWEA estimates exhibited positive correlation with measured values of beaver pond volumes and areas. For individual ponds, volumes

estimated by BD-SWEA did not differ significantly from measured pond volumes (p = 0.85), and, at the watershed scale, BD-SWEA accounted for 83% of variation in the total area inundated by beaver ponds. When coupled with existing models of beaver dam capacity, BD-SWEA will provide opportunities to assess potential ecological and hydrological benefits and challenges of beaver reintroduction and beaver-based restoration techniques.

INTRODUCTION

On many landscapes in the western United States, dams built by North American beaver (*Castor canadensis*) are prevalent features that have profound impacts on surrounding ecosystems (Rosell *et al.*, 2005). The impacts of these dams on riparian ecosystems have been well conceptualized (Burchsted et al., 2010; Johnston and Naiman, 1987; Naiman et al., 1988), and field studies confirm the ability of beaver to beneficially alter physical (Gurnell, 1998; Majerova *et al.*, 2015; Pollock *et al.*, 2014; Stout *et al.*, 2016) and ecological (Bouwes *et al.*, 2016; Rosell *et al.*, 2005; Runyon *et al.*, 2014) aspects of riparian and aquatic systems. The degree to which beaver may alter these systems is driven by the size, density (i.e. spacing between dams; typically reported in dams/km), and frequency of dam types beaver construct in dam complexes (Burchsted *et al.*, 2010; Johnston and Naiman, 1990b; Karran *et al.*, 2016). A large body of literature is focused on identifying and quantifying the effects of beaver dams on the surrounding environment (Barnes and Dibble, 1988; Collen and Gibson, 2000; Gurnell, 1998; Hood and Bayley, 2008; Rosell *et al.*, 2005). However, there is a surprising paucity of basic empirical data regarding the drivers of these impacts (e.g. the size of individual dams and the structure of dam complexes) at scales larger than a stream reach (~1 km). There is growing interest in using beaver as agents to restore degraded streams (Bouwes *et al.*, 2016; Burchsted *et al.*, 2010; Pollock *et al.*, 2011, 2015, 2014). Similarly, many have argued the ecosystem engineering of beavers through their dam building activity could potentially buffer some anticipated effects of climate change (Hood and Bayley, 2008; Majerova *et al.*, 2015; Nyssen *et al.*, 2011; Puttock *et al.*, 2017). Thus, a more robust empirical understanding of the basic morphometric characteristics of beaver dams that drive the magnitude of desired impacts is necessary to reliably identify where, and to what degree, beaver dams may provide anticipated benefits. Moreover, if we want to plan and assess the potential impacts such beaver dam building activity could have when tens of thousands of dams are returned to riverscapes, we need to be able to accurately simulate and estimate the extent and scope of these impacts. Empirical data are critical for the parameterization, calibration, and/or validation of such simulation modeling efforts to quantify the potential role of beaver dam building activity. Such context is not only critical in planning for restoring physical and ecologic processes with the help of beaver, but also developing realistic expectations for what the impacts may be on water resources management.

The size of beaver dams drives their ability to impact adjacent physical and ecological systems. In general, the length and height of a beaver dam are positively correlated with the surface area and volume of the resulting pond (Beedle, 1991; Karran *et al.*, 2016). Increasing the surface area and temporary storage volume of water in a lotic system alters stream hydraulics resulting in changes to grain size distributions, temperature regimes, biogeochemical cycles, evaporation, geomorphic units, and fish habitat (Bouwes *et al.*, 2016; Gurnell, 1998; Puttock *et al.*, 2017; Stout *et al.*, 2016; Woo and Waddington, 1990). Larger (i.e. taller and longer) beaver dams may also have greater impacts on local groundwater tables and flow patterns (Feiner and Lowry, 2015; Lowry, 1993; Westbrook *et al.*, 2006) which in turn affect the growth and composition of vegetation communities (Johnston and Naiman, 1990a; Runyon *et al.*, 2014; Wolf *et al.*, 2007), their associated wildlife (Bouwes *et al.*, 2016; Cooke and Zack, 2008), and evapotranspiration rates (Woo and Waddington, 1990). Based on values reported in the literature, the majority of beaver dams range from 0.2 m to 2.2 m tall with a mean height around 1.0 m (Table 2.1), but may be taller than 5 m (Grasse and Putnam, 1955). Dam lengths exhibit more variability, generally ranging from 0.5 m to 308 m with means between 16 m – 69 m reported (Table 2.1), however, a dam 700 m long has also been observed (Ives, 1942). Where healthy beaver populations exist, dams may occur at densities of up to 40 per km (an average of one dam every 25 m), and densities have been documented over large areas by identifying dams and ponds from aerial imagery (Hood and Larson, 2015; Macfarlane *et al.*, 2017; Puttock *et al.*, 2015). Other studies have examined and modeled the effects of beaver dams over relatively large spatial scales (Hood and Bayley, 2008; Johnston *et al.*, 1990; Macfarlane *et al.*, 2017).

Despite many studies on effects of beaver dams, studies documenting basic empirical information regarding the size of beaver dams have been somewhat limited in geographic extent and/or sample size when compared with the geographic distribution and prevalence of beaver dams. Many studies provide more detailed quantification of dams and ponds (e.g. Beedle, 1991; Karran et al., 2016), or collect data for purposes other than quantifying dams themselves (e.g. fish passage and habitat; Collen and

Gibson, 2000; Lokteff et al., 2013; Pollock et al., 2011). Beaver primarily build dams for three purposes (Muller-Schwarze, 2011). (1) To inundate entrances to lodges and tunnels providing shelter for the individuals of the colony maintaining the dams, (2) to inundate food caches that provide forage during winter months, and (3) to increase the colony's foraging range by providing additional inundated areas which serve as refugia from predators and corridors for transportation of food and building materials. These functional differences between dam types suggest there may be height difference between them, with dams containing a food cache, lodge, or tunnel being larger as they must create an impoundment deep enough to inundate these features. Herein we differentiate beaver dam types as primary or secondary. Primary dams are those dams which host a lodge and/or food cache, and are generally of larger size and often extend onto and inundate adjacent floodplains. By contrast, secondary dams are all other dams. Of the studies reported in Table 2.1 none differentiate between the sizes of primary and secondary dams, which highlights a general knowledge gap regarding the size differences among dam types and the relative abundance of each. While dam type may not be as important as dam density in driving the effects of dams, size differences between primary and secondary dams likely affect the impacts of individual dams, warranting further exploration. From a modeling perspective, identifying differences in size and occurrence frequency between dam types is critical for model parameterization to ensure accurate estimation of potential conditions.

The density of dams along a stream network is another determinant of the degree to which beaver may alter ecosystems, with higher dam densities generating greater effects (Burchsted *et al.*, 2010; Cooke and Zack, 2008; Johnston and Naiman, 1990a).

Many studies have documented dam densities from field observations and aerial imagery (Cooke and Zack, 2008; Hood and Bayley, 2008; Puttock *et al.*, 2015), and recent efforts have produced models to spatially estimate maximum dam densities that could be supported by stream reaches (Macfarlane *et al.*, 2017). Such dam capacity models consider the vegetative and hydrologic attributes of streams to identify where and to what extent beaver dams may be built and persist. Dam capacity models differ from habitat models in that they consider the environmental variables governing construction and maintenance of beaver dams instead of the environmental factors necessary to sustain beaver populations, though considerable overlap may exist. Beaver dam capacity models identify where and to what extent beaver dams may currently exist or be constructed in the future, but do not address what the effects of dam construction may be. One method to identify the potential effects of beaver dam construction would be scenario-based modeling in which a dam capacity model provides a tractable method to generate scenarios of dam density. In order to determine the potential effects of beaver dam construction at a given location, the location of the dam and the size and extent of the resulting pond must be identified. While densities have been widely documented, the variables describing the spatial configuration of dams have not. Beaver live in colonies consisting of family units (Gurnell, 1998; Townsend, 1953), and are somewhat territorial (Aleksiuk, 1968; Müller-Schwarze and Heckman, 1980), indicating there should be some spatial structure to how dams are distributed throughout a riverscape. Generally, a beaver colony maintains a primary dam and multiple surrounding secondary dams often referred to as a dam complex (Gurnell, 1998; Muller-Schwarze, 2011). The number of dams per dam complex would provide some insight into spatial structure and configuration of beaver dams, and is necessary to develop methods for scenario-based modeling of beaver dam impacts. With estimates of dam locations and dam heights the resulting beaver pond could be modeled by leveraging a digital elevation model to represent the land surface, thus predicting location specific inundation extents and water depths for ponds resulting from beaver dam construction.

While various methods have been implemented for quantifying the size and impacts of existing beaver dams, predictive methods have not been applied to forecast the potential effects of beaver dam construction. As beaver and beaver-mimicking methods are increasingly being used in stream restoration strategies (Bouwes *et al.*, 2016; Pollock *et al.*, 2014) the ability to identify the potential effects of restoration efforts could greatly increase the efficacy of such efforts. We suggest predictive modeling of the effects of beaver dams has been precluded by a lack of empirical data describing basic morphometries of beaver dams and models estimating the number of beaver dams riverscapes may support to identify where and to what extent beaver dam building may occur.

The purpose of this paper is to supplement existing empirical data describing beaver dam morphometry and use these empirical data, along with readily available topographic data, to develop a model predicting the volume of surface water stored by a given beaver dam. We conduct rapid field assessments (e.g. Camp and Wheaton, 2014) of beaver dams to supplement existing empirical data describing the size and condition of beaver dams and beaver dam complexes. These data also describe and differentiate between the size attributes of primary and secondary dams, which have not been reported by previous studies. Using these empirical data, we develop the Beaver Dam Surface

Water Estimation Algorithm (BD-SWEA), a spatially explicit methodology for modeling the size (area and volume) of beaver ponds from digital elevation models (DEMs) and empirical dam height distributions. When coupled with spatially explicit estimates of the number of beaver dams riverscapes may support (e.g. Macfarlane *et al.*, 2017), BD-SWEA will provide opportunities to assess the potential impacts of beaver-based restoration projects and beaver reintroductions. Our data and methodologies can be further extended and/or improved to examine the impacts of beaver dams on multiple systems and processes at various spatial scales.

Table 2.1. Summary of dam heights and dam lengths reported from studies examining multiple beaver dams constructed by North American beaver (*Castor canadensis*). Adapted from Beedle (1991). Note that studies examining single dams have reported dam heights over 5 m (Grasse and Putnam, 1955) and dam crest lengths up to 700 m (Ives, 1942).

			Crest Length (m)		**Dam Height (m)**	
Author(s)	**Year**	**Dam Count**	**Mean**	**Range**	**Mean**	**Range**
Karran et al.	2016	40	69	3 - 308	0.90	0.2 - 2.0
Majerova et al.	2015	10	-	-	1.00	-
Levine and Meyer	2014	4	-	10 - 36	-	1.4 - 1.7
Lokteff et al.	2013	21	-	-	0.99	0.3 - 2.0
Wesbrook et al.	2006	2	19	8 - 30	1.25	0.8 -1.7
Meentemeyer and Butler	1999	10	19	3 - 52	0.94	0.4 - 1.4
Beedle	1991	44	32	2 - 132	0.70	0.5 - 1.5
McComb et al.	1990	14	-	-	0.55	-
Bryant	1983	7	24	5 - 46	1.00	0.8 - 2.2
Townsend	1953	-	-	0.5 - 13	-	0.1 - 1.5
Smith	1950	30	27	-	-	-
Scheffer	1938	23	13	2 - 37	0.94	0.3 - 2.1
Dugmore	1914	-	-	91 - 152	-	-
Morgan	1868	9	19	-	-	0.3 - 1.5
Mean	**-**	**-**	**27.8**	**14 - 90**	**1.18**	**0.5 – 1.8**
Range	**-**	**-**	**13 - 69**	**0.5 - 308**	**0.55 – 1.25**	**0.1 – 2.2**
Total	**-**	**214+**	**-**	**-**	**-**	**-**

METHODS

Herein we present the methods used to develop a spatially-explicit model, the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA), to estimate the extent and volume of ponds created by construction of beaver dams. As stated above, development of such a model requires an empirical understanding of beaver dam size (primarily dam height) for parameterization, calibration, and validation. In addition to empirical descriptions of beaver dams, representation of topography at the location of a given dam is necessary to estimate the size and volume of the pond created by the given dam. Digital elevation models (DEMs) of 1/3 arc second (approximately 10 m) resolution are available for the conterminous US. However, given the area of beaver ponds, which may be less than the 100 m^2 resolution of these DEMs, it is necessary to leverage datasets of higher resolution in concert with observed beaver pond measurements to accurately develop and validate a predictive model. The following describe the data and methods implemented to develop, parameterize, calibrate, and validate BD-SWEA.

Study Sites

We selected the Little Bear – Logan River watershed as our area of modeling interest (Figure 2.1) because development of progressive beaver management plans for private companies (Portugal *et al.*, 2015a) and government institutions (Portugal *et al.*, 2015b) indicate a general interest in conserving beaver populations in the watershed. The Utah Division of Wildlife Resources has also established beaver protection areas in this watershed where hunting and trapping have been temporarily suspended resulting in beaver dam complexes that have persisted for multiple years (UDWR, 2010), providing ideal sites to observe and measure beaver dams. Past research efforts in the watershed examining the impact of beaver and their dams have also provided numerous field observations and detailed topographic surveys of beaver dams and beaver dam complexes which are crucial to development and validation of BD-SWEA (e.g. Lokteff et al., 2013; Majerova et al., 2015). Additionally, the close proximity of the Little Bear – Logan River watershed to Utah State University allowed more opportunity for field validation of BD-SWEA results and data collection for BD-SWEA parameterization.

Overall, beaver dam data were collected from various locations in Utah, Idaho, and Oregon (Figure 2.1), and these study sites were selected based on the following considerations. The Bridge Creek and Temple Fork sites were selected because high-resolution digital elevation models (DEMs) from total station (TS) and real-time kinematic (RTK) global positioning system (GPS) surveys (0.1 m) and light detection and ranging (LiDAR) flights (1.0 m) (NCALM, 2011; Woolpert Inc., 2012) available at these locations provided data at multiple spatial resolutions with which validate BD-SWEA. A high-resolution DEM from a RTK-GPS survey was also available for Curtis Creek (Majerova *et al.*, 2015), and 1 m LiDAR DEMs were available for the North Fork of the Ogden River (NFO) and its tributaries (Utah State University LASSI Service Center, 2012). Beaver Creek, Rock Creek, and the South Fork of the Little Bear River are located within the Little Bear – Logan River watershed (HU8), the area of modeling interest. Data were collected at these sites to increase the sample size of dams used to parameterize BD-SWEA. Data from Birch Creek, Box Creek, Huff Creek, and the Santa Clara River were collected opportunistically. In all, we collected data via field surveys or from existing topographic surveys for 561 beaver dams (Table 2.2). For an additional dataset to validate pond area estimates from BD-SWEA, we collected 1211 beaver dam locations and pond areas throughout the Little Bear – Logan River watershed by conducting a census of beaver dams and digitizing dams and the area inundated by resulting ponds from aerial imagery.

Table 2.2. Summary of data collection sites and the type(s) of data collected, or available, for each site (Figure 2.1).

Site Name	**Data Type**	**Number of Dams**
Beaver Creek	Field survey	62
Birch Creek	Field survey	5
Box Creek	Field survey	21
Bridge Creek	0.1 m TS/RTK_GPS surveys,	37
	1 m LiDAR	-
Curtis Creek	Field survey,	37
	0.1 m RTK_GPS surveys	8
Huff Creek	Field survey	29
North Fork Ogden River	Field survey	108
	1 m LiDAR	-
Rock Creek	Field survey	102
Santa Clara River	Field survey	10
South Fork Little Bear River	Field survey	9
Temple Fork	Field survey,	117
	0.1 m TS/RTK_GPS surveys,	16
	1 m LiDAR	-
Little Bear – Logan River watershed	Aerial imagery	1211
Total Dams		**1772**

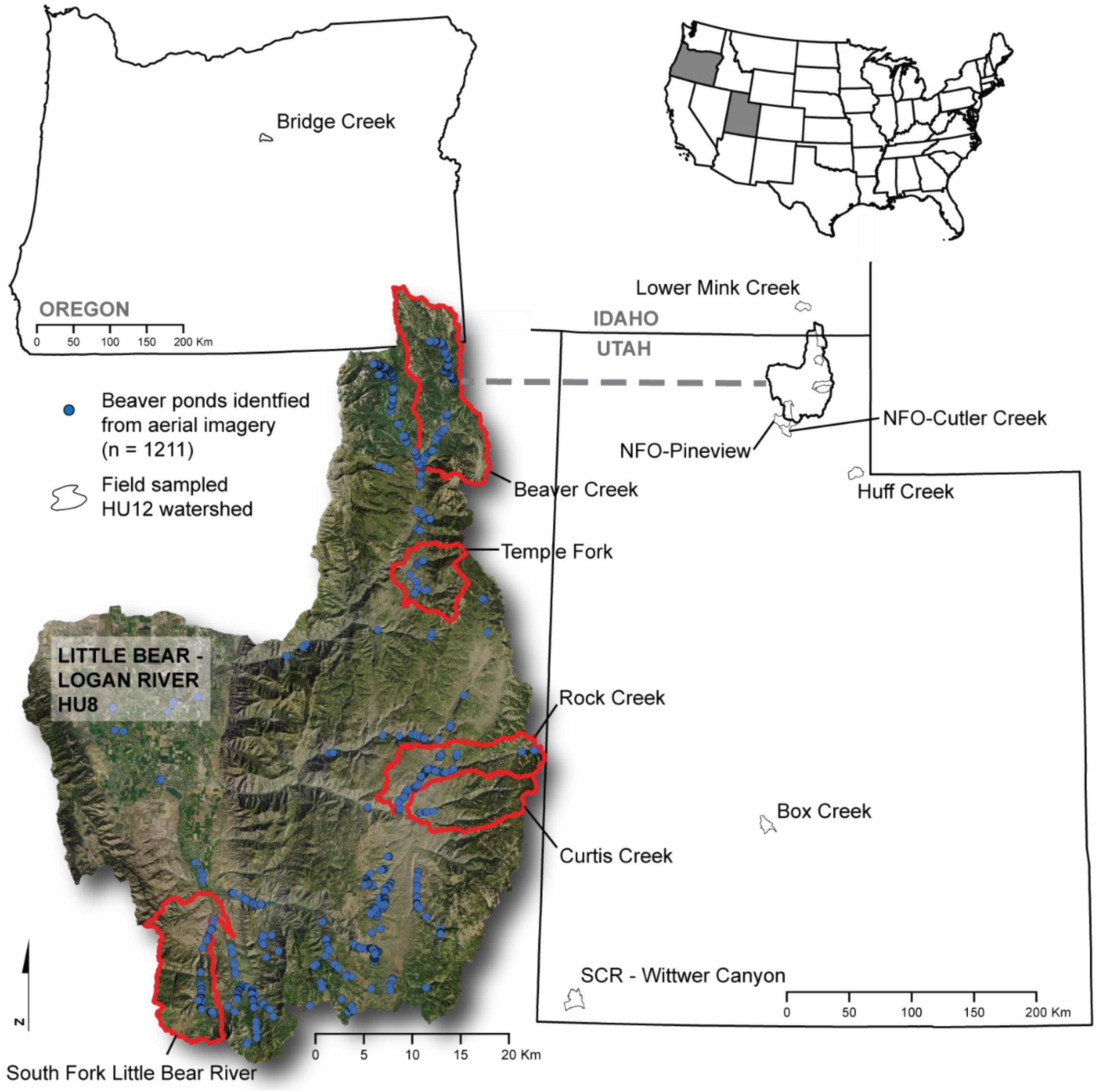


Figure 2.1. Utah, Idaho, and Oregon HU12s where topographic or field data were collected, with an inset of the Little Bear – Logan River HU8 showing locations of dams identified from aerial imagery. The North Fork of the Ogden River is abbreviated as NFO, and the Santa Clara River as SCR.

Data Collection

Rapid field assessments. In the field, we visited beaver dam locations and collected data describing the location, height, type, condition, and construction material of each beaver dam via rapid assessments using iPads (e.g. Camp and Wheaton, 2014) equipped with GIS software (Table 2.3). An observer would walk upstream along the stream until they observed a beaver dam. At each beaver dam, the observer would record the dam height, dam type, dam condition, dam status, and the primary material used to construct the dam (Table 2.3). Dam heights were measured from the tallest point on the dam crest to the lowest point on the streambed downstream of the dam (Beedle, 1991; Majerova *et al.*, 2015; Townsend, 1953). Dams that inundated a pond containing a beaver lodge or a food cache were classified as primary dams, all other dams were classified as secondary. Dam condition was classified as intact, breached, or blown-out. Breached dams were any dam where a partial removal or loss of material from the dam crest resulted in a lowering of the pond water surface elevation. By contrast, blown-out dams were defined as enough of the dam being breached or washed away that the dam no longer backs up water (note that this can occur without the complete removal of all the material comprising the dam – e.g. as in an end cut). Dam status was identified by the presence of fresh vegetation cuttings, recent mud piles or scent mounds, and/or active skid trails at a site. As beaver are most active in autumn while they prepare for winter, and all of our surveys occurred prior to September, evidence of recent beaver activity was lacking at many sites creating difficulty in determining if dams were actively being used by beaver. Observers also recorded the pond area by walking around the area inundated by the dam and recording the path on an iPad at the Temple Fork and NFO study sites. Pond areas were recorded at these sites because 1 m LiDAR DEMs available for these watersheds made them important sites to test BD-SWEA on DEMs of multiple resolutions. At the Temple Fork and NFO study sites a near complete field census of beaver dams was conducted, where all sections of streams with public access were surveyed. In all rapid field assessments were conducted for 500 beaver dams (Table 2.2).

Table 2.3. Variables collected during rapid beaver dam surveys, and value options for each variable. Pond areas were only collected at the Temple Fork and North Fork of the Ogden River study sites where LiDAR DEMs were available.

Variable	**Description**	**Values**
Dam height	Measured from the top of the dam to the stream thalweg downstream of the dam	Continuous (m)
Pond area	Surface area of the water impoundment created by a beaver dam at observed stage	Continuous (m^2)
Dam type	Primary dams create a pond that inundates a lodge or a food cache	Categorical (Primary, Secondary)
Dam condition	Measure to the structural status of the dam	Categorical (Intact, Breached, Blown-out)
Dam status	Were beaver currently occupying or maintaining the dam?	Categorical (Active, Inactive)
Primary construction material	Material that was used most extensively in construction of the dam	Categorical (Aspen, Conifer, Cottonwood, Willow, Riparian Shrub, Riparian Tree, Other Shrub, Other Tree, Sagebrush, Grass, Mud, Rock)

Dam complexes. We define dam complexes as a single primary dam, and all secondary dams spatially associated with that primary dam, and that are maintained by the colony occupying the primary dam. Dam complexes were delineated using geographic information software (GIS) to attribute all dams associated with a complex, and dams of all conditions (intact, breached, and blown-out) were included when delineating complexes. Dams are considered to be associated with the same dam complex when the areas that they inundate through backwater ponding and inundation from the dams, are only separated by beaver dams. In other words, the backwater extent upstream of dams within a complex of dams in series all typically backwater to the base of other dams within that complex. Some complexes have beaver dams in parallel (i.e. on different anabranches or side channels), and these are considered part of the same complex when they are connected by either beaver-dug canals or the same backwater criterion above. In many instances, dam complexes were clearly spatially segregated with obvious distance between the areas ponded in each, providing easy identification of which dams belong to which complex (Figure 2.2A). For cases where boundaries between complexes were not clearly defined, secondary dams were split between the complexes at a roughly equal distance between two primary dams (Figure 2.2B). In other instances, secondary dams did not exist in close proximity to a primary dam. Lack of primary dams may be attributed to several explanations: Observers may not have detected lodges or food caches that were concealed by thick vegetation. Beaver may dig tunnels and create lodges underground in streambanks instead of mounding mud and wood to create a lodge. Observed dams may have been part of complex that was under construction but not yet completed. Or construction on a dam complex may have been initiated but not completed. In these cases, complexes were delineated by grouping secondary dams together according to their spatial configuration and the backwater criterion (Figure 2.2C).

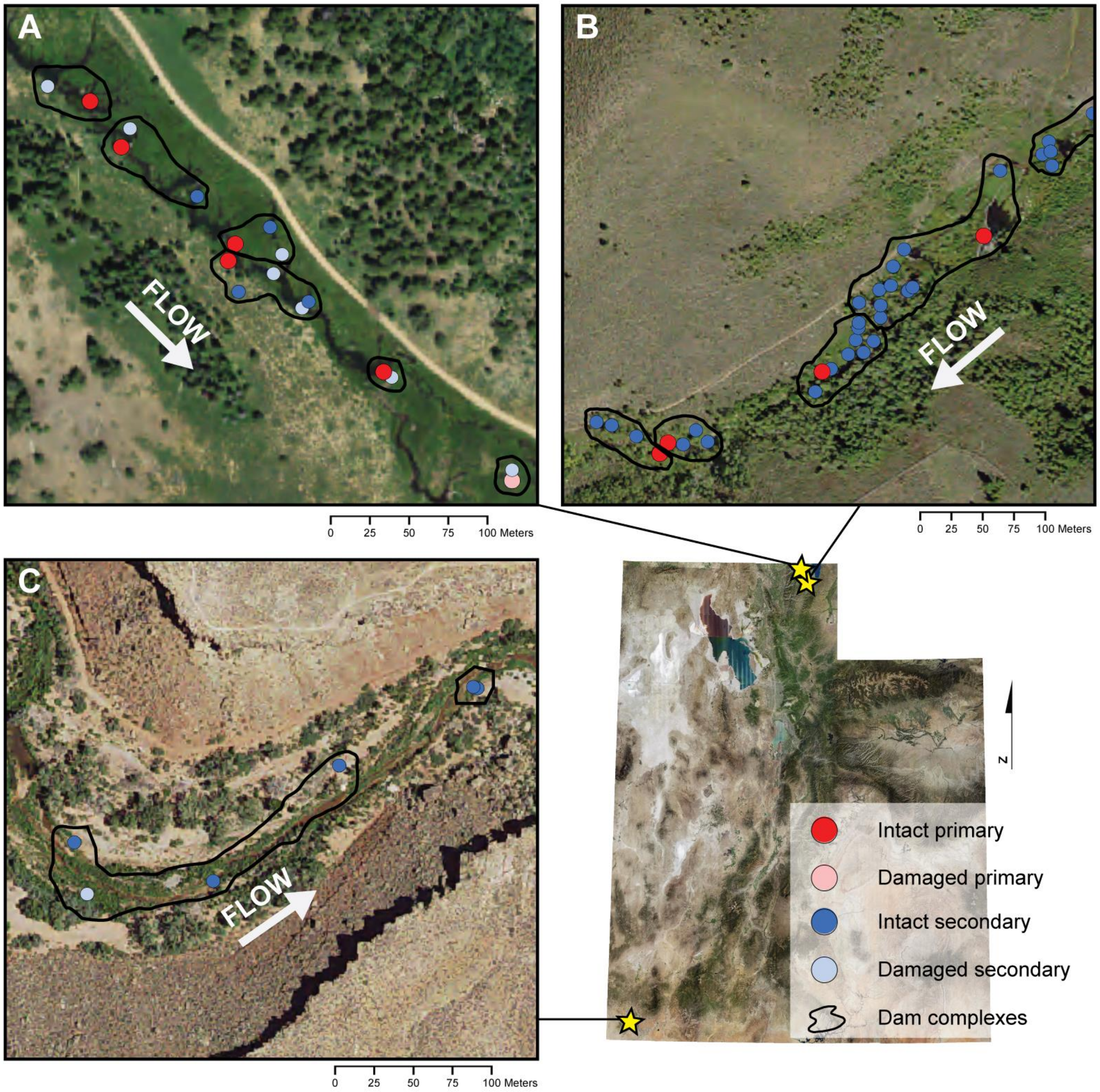


Figure 2.2. Examples of dam complex delineation for dam complexes where (A) complex boundaries are relatively discrete, (B) complex boundaries are somewhat arbitrary, and (C) complexes do not contain primary dams.

Data extraction from high-resolution topography. In addition to collecting data by rapid field survey, we also leveraged existing high resolution DEMs of beaver ponds, which had been collected for previous studies (e.g. Bouwes *et al.*, 2016; Majerova *et al.*, 2015), to extract beaver dam and pond morphometries necessary to estimate beaver pond volumes. Estimates of beaver pond volumes and the height of the corresponding dam were used to validate BD-SWEA. High resolution DEMs were collected in the field with TS and RTK-GPS methods for the Bridge Creek, Curtis Creek, and Spawn Creek study sites (Figure 2.3). Surveys of Bridge Creek and Curtis Creek also produced water surface elevation (WSE) rasters from which water depth was calculated (DEM subtracted from WSE). The process for extracting morphometries from these topographic data consisted of two parts. First, using GIS software, we digitized the dam crest, an area representing the base of each dam, and an area generously representing the maximum plausible inundation extent of each pond for each beaver dam (Figure 2.4). Second, python scripts were developed and executed to extract the morphometric measurements described in Figure 2.3. Automation through the python programming language was used to ensure consistency with calculation methods. The morphometry definitions implemented to extract pond and dam morphometries are described in Table 2.4 and we have made the python scripts available at https://github.com/khafen74/bd-morphometry-extraction. In all, morphometrically derived dam heights, dam crest lengths, maximum pond areas, and maximum pond volumes were calculated for 56 beaver dam/pond combinations (only a partial DEM was available for four ponds allowing only dam heights and crest lengths to be calculated).

Table 2.4. Definitions of morphometric measurements extracted from high-resolution digital elevation models (DEMs) and water surface elevation (WSE) rasters of beaver ponds. Visual explanations of some definitions are presented in Figure 2.3.

Feature	Definition	WSE required	Figure 2.3 Reference
Dam crest elevation	The maximum elevation of the DEM or WSE raster (whichever is greater) within a 0.15 m horizontal buffer of the digitized dam crest	No	A
Maximum pond extent, or maximum pond area	All raster cells within the digitized maximum pond extent with an elevation less than the dam crest elevation (see Figure 2.4)	No	-
Actual pond extent, or pond area	Delineated by extracting all raster cells within the digitized maximum pond extent with an elevation value less than the dam crest elevation and a water depth value greater than zero	Yes	Pond perimeter
Minimum pond elevation	The minimum elevation within the extracted maximum pond extent	No	C
Dam base elevation	The minimum elevation within the digitized dam base area (see Figure 2.4)	No	D
Dam height	Dam base elevation subtracted from dam crest elevation	No	2
Maximum pond volume	The elevation value at a given cell subtracted from the dam crest elevation, summed across all cells within the maximum pond extent, and multiplied by cell width and cell height	No	-
Actual pond volume	The sum of water depth for all cells within the actual pond extent, multiplied by cell width and cell height	Yes	-
Pond water surface elevation	The mean WSE value for all cells within the actual pond extent	Yes	B
Head difference	WSE value at the dam base subtracted from the pond WSE	Yes	1

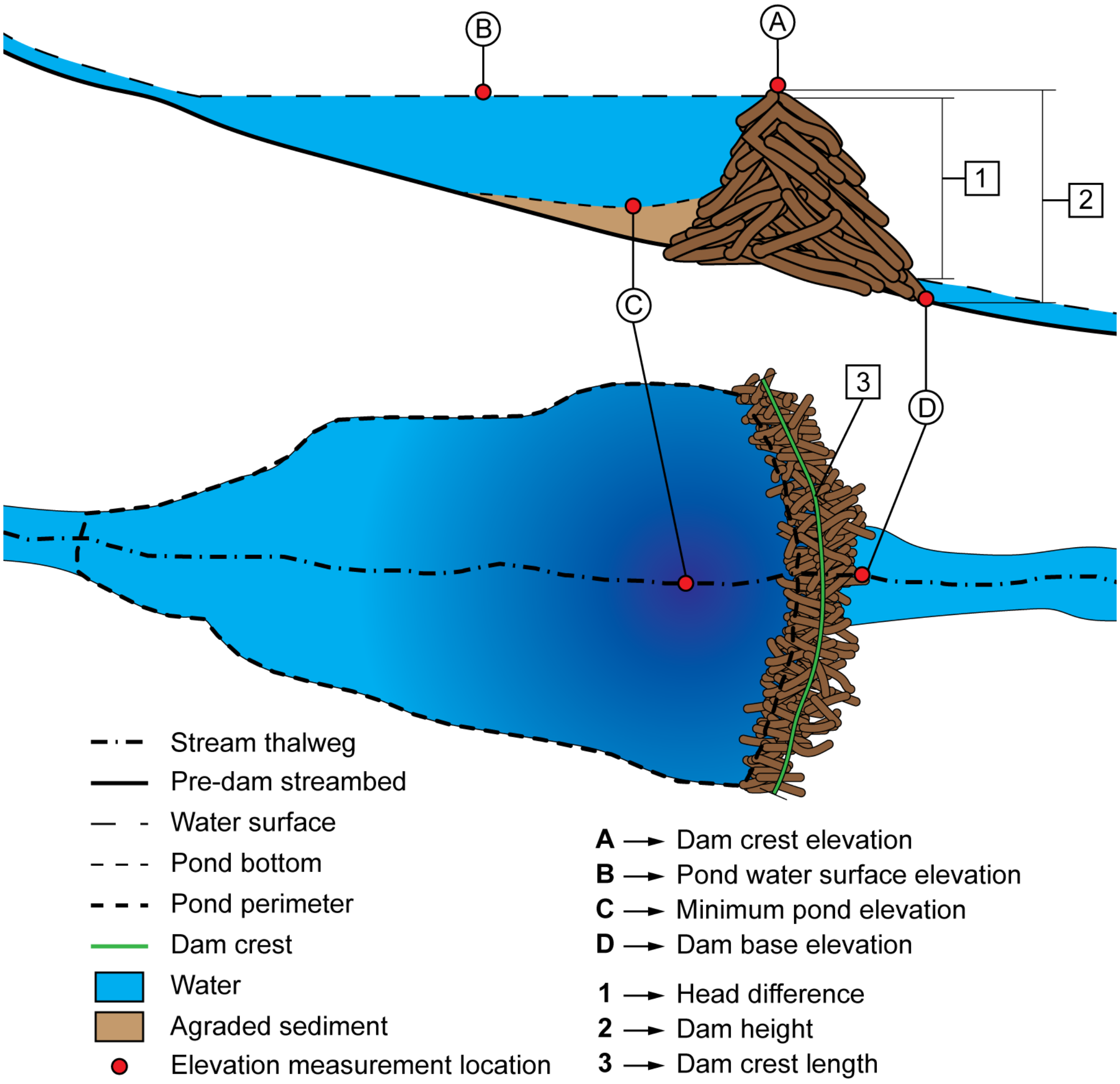


Figure 2.3. Measurements taken in the field and derived from high resolution topography. Table 2.4 provides definitions of measurements.

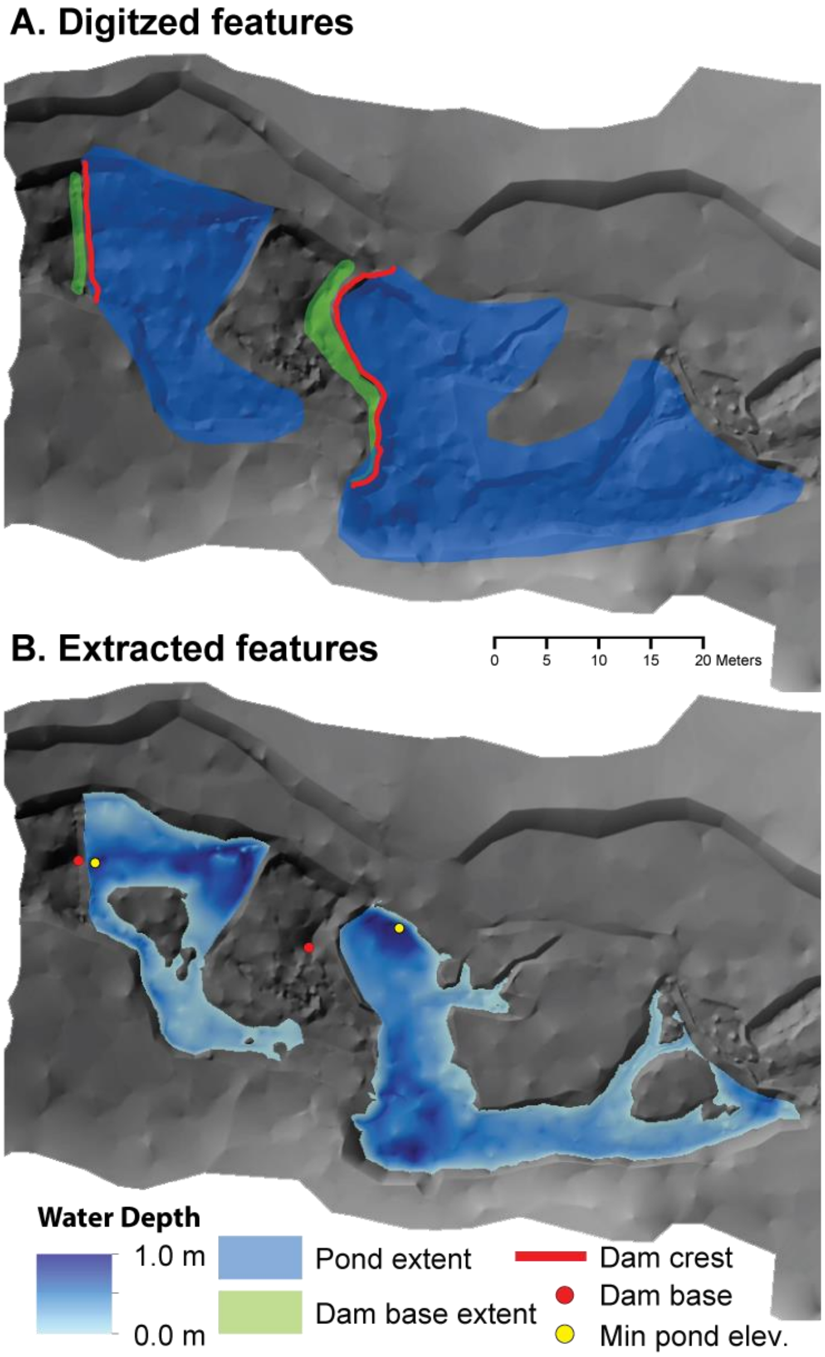


Figure 2.4. Example of (A) manually digitized beaver dam and beaver pond input features of maximum plausible inundation extent (roughly digitized), beaver dam crest, and a region reflecting the base of the beaver dam. These digitized features were used to extract estimates of dam and pond morphometries from high resolution topography, and the resulting refined pond extents, minimum pond elevation, water depth, and dam base locations are shown in B. These examples are illustrated on a 0.1 m DEM.

Data Analysis

Rapid field assessments and dam complexes. With a t-test, we evaluated differences in dam heights between primary and secondary dams. Using analysis of variance (ANOVA) and Tukey Honestly Significant Difference (HSD) tests we tested for differences in dam height between 12 digit hydrologic units (HU12), and the different construction materials of dams. All tests were conducted at a 95% confidence level. We also provide overall distribution parameters for all dams, primary dams, and secondary dams, and report their relative frequency. Similarly, we present the distribution parameters for the number of dams per dam complex.

Data from high-resolution topography. Using the data extracted from high-resolution topography, we fit a multiple linear regression model describing pond volume as a function of dam height and reach slope (percent). Reach slope was calculated (in percent) from 10 m National Elevation Dataset (NED) DEMs and extracted to National Hydrography Dataset flowlines segmented to 300 m stream reaches following the methodology of Macfarlane et al. (2017). We chose this measurement of slope as it could easily be applied to the modeling methodology for BD-SWEA, allowing this empirical model to help constrain any erroneous model outputs. For fitting of the regression model, measurements of maximum pond volume were log transformed, and dam height measurements were square root transformed to meet normality assumptions. Slope data were approximately normal. We chose not to include other predictor variables that would require *a priori* knowledge of the pond (e.g. pond area, pond depth) as these parameters are not available in a predictive model context, though they are important predictors of pond volume (Karran *et al.*, 2016).

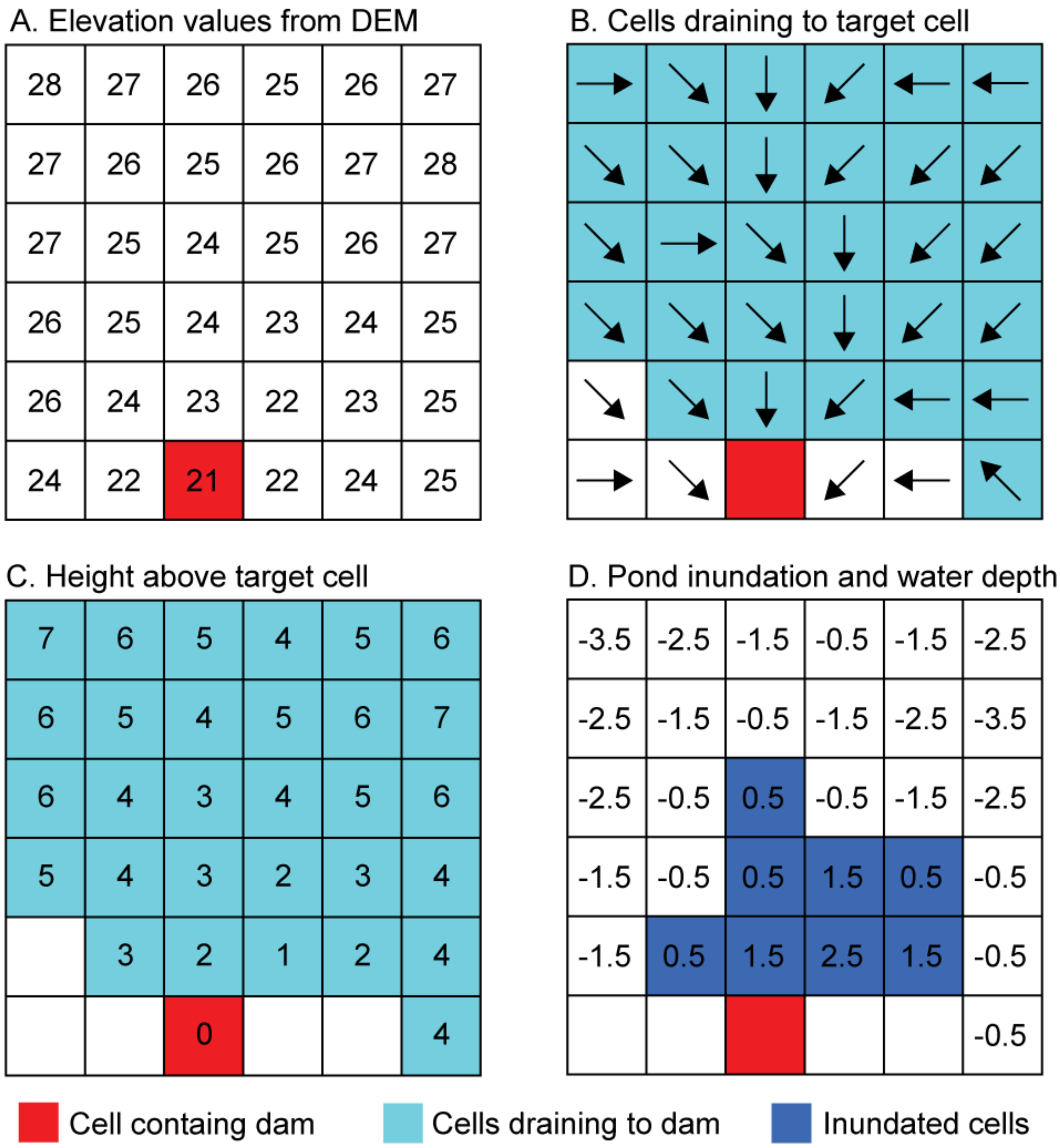
The BD-SWEA Model

We expect the volume of water inundated by a beaver dam and the extent (i.e. area) of inundation to be a function of the height of a beaver dam and the topography that is inundated. Estimates of beaver dam heights can be obtained from reported empirical distributions, and topography can be represented by various DEM products, some of which are available for the entire US. With these inputs we develop a predictive model to estimate the areal extent and surface volume of beaver ponds resulting from beaver dam construction. We implement the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA), which is based on a reverse implementation of the height above nearest drainage (HAND) algorithm (Nobre *et al.*, 2011; Rennó *et al.*, 2008), to determine the inundation extent and volume of water inundated by a beaver dam using inputs of beaver dam height and a DEM to represent topography. The BD-SWEA methodology works as follows. From a DEM, an eight-direction flow direction raster is created. A cell is selected to represent the location of a beaver dam of a given height (Figure 2.5A). Using the flow direction raster, all cells draining to the location of the beaver dam are identified (Figure 2.5B). The height of each cell above the cell containing the dam is calculated as the elevation of the cell containing the dam subtracted from the elevation of the cell draining to the dam (Figure 2.5C). For each cell the water depth is then calculated as the height of the cell above the dam's location subtracted from the height of the dam (Figure 2.5D). Positive values represent water depths and values less than or equal to zero represent cells that would not be inundated by the dam. We applied BD-SWEA using 1 m LiDAR DEMs available at the NFO, Temple Fork, and Bridge Creek sites and 1/3 arc second (~10 m) DEMs available from the National Elevation Database (NED). In our application of BD-SWEA we also included a drainage area raster, which included only cells with a contributing area of greater than 1 km, to represent a stream network. Modeled beaver dams were moved to the nearest cell on this network and pond area and volume were modeled with BD-SWEA at that location. The algorithms for this workflow were implemented and automated using the C++ programming language with the Geospatial Data Abstraction Library (GDAL) for raster manipulation and management (GDAL Development Team, 2014), code is available at https://github.com/khafen74/bd_h2o.

BD-SWEA Validation

Using field collected dam locations and dam heights as inputs for BD-SWEA, we modeled the area of dams surveyed in the field. These simulations were conducted using both 1 m and 10 m DEMs as model inputs. We assessed results with a linear hypothesis test to simultaneously determine if the intercept and slope of the regression line between the modeled and observed data differed from zero and one, respectively. As negative values of area are not possible, and all observed areas with zero change in area (i.e. not beaver pond locations) were not modeled, we also fitted a regression with an intercept of zero and with a Student’s t-test tested if the slope of the modeled regression line differed from a slope of one.

With prediction intervals from the multiple regression model relating pond volume to dam height and reach slope (see above), we also added automated, in-model validation of BD-SWEA. After modeling a pond from input parameters, the volume of that pond was assessed to determine if it fell within the regression prediction interval for its given dam height and reach slope. If the pond volume fell within the regression’s prediction interval nothing was done. If the pond volume fell outside of the prediction



A. Elevation values from DEM

28	27	26	25	26	27
27	26	25	26	27	28
27	25	24	25	26	27
26	25	24	23	24	25
26	24	23	22	23	25
24	22	21	22	24	25

B. Cells draining to target cell

→	↘	↓	↙	←	←
↘	↘	↓	↙	↙	↙
↘	→	↘	↓	↙	↙
↘	↘	↘	↓	↙	↙
↘	↘	↓	↙	←	←
→	↘	🟥	↙	←	↖

C. Height above target cell

7	6	5	4	5	6
6	5	4	5	6	7
6	4	3	4	5	6
5	4	3	2	3	4
	3	2	1	2	4
		0			4

D. Pond inundation and water depth

-3.5	-2.5	-1.5	-0.5	-1.5	-2.5
-2.5	-1.5	-0.5	-1.5	-2.5	-3.5
-2.5	-0.5	0.5	-0.5	-1.5	-2.5
-1.5	-0.5	0.5	1.5	0.5	-0.5
-1.5	0.5	1.5	2.5	1.5	-0.5
		🟥			-0.5

🟥 Cell containg dam

🟦 Cells draining to dam

🟦 Inundated cells

Figure 2.5. The Beaver Dam Surface Water Estimation Algorithm (BD-SWEA) for modeling inundation extent and water depth of a pond created by a dam 3.5 units tall, the dam's elevation above sea level is 24.5 units. (A) DEM values for area of interest with red indicating the location of the dam. (B) D8 flow directions derived from the DEM determine which cells drain the cell containing the dam. (C) The height of each cell above the cell containing the dam. (D) Inundation extent of the pond

interval, however, the dam height was iteratively adjusted by 0.1 m increments and BD-SWEA recalculated pond volume until the pond volume approached the value predicted by the regression. If the dam reached a height of less than 0.1 m or greater than 4.0 m during this process the iterative adjustment was aborted and the dam height and pond volume were returned to their original values.

We also tested the performance of BD-SWEA using 10 m NED DEMs to model ponds at the 1211 dam locations digitized from aerial imagery. As dam heights were not linked to pond areas for these ponds, we randomly classified each dam to be modeled as primary or secondary based on the frequency observed in field observations (15% primary dams, 85% secondary dams). To determine the height of the modeled dam, we randomly sampled the distribution of observed primary or secondary dam heights 1000 times and used the median value of these samples as the modeled dam height. Pond-specific dam heights were not available for these digitized pond areas greatly limiting our ability to accurately model the area of individual ponds, so we summed the inundated and model areas by HU12 and validated based on this measure. For the final validation test, we modeled the dam locations and dam heights extracted from high-resolution topography on both 1 m and 10 m DEMs, this time comparing the modeled and observed pond volumes. Once again, we simultaneously tested for deviation from an intercept of zero and slope of one between the modeled and observed data.

RESULTS

Field Data

Overall, we analyzed data from 500 beaver dams collected via rapid field assessment (Table 2.4). Of the dams surveyed, 85% (425) were secondary dams, leaving 15% (75) as primary dams. As for dam condition, 65% (322) of dams were intact, 19% (97) breached, and 16% (81) blown-out. The majority of blown out dams (55) occurred in the Cutler Creek-North Fork Ogden River HU12 (Table 2.4).

Heights of intact beaver dams ranged from 0.12 m – 2.80 m with a mean of 0.95 m and a standard deviation of 0.39 m. Dam heights most closely followed a square root normal distribution with mean 0.96 and variance 0.20 (Figure 2.6). The square root distribution is meaningful as it prevents negative values for dam heights. Primary and secondary dams also followed square root normal distributions with means 1.14 and 0.92, and variances 0.20 and 0.17, respectively (Figure 2.6). Heights of primary dams were significantly taller than secondary dams ($t = 7.32$, $df = 74$, $p < 0.0001$) averaging 1.33 m with a standard deviation of 0.47 m in comparison to secondary dams which averaged 0.87 m with a standard deviation of 0.31 m (Figure 2.7). Analysis of variance indicated significant differences in dam height between HU12s ($f = 2.51$, $df = 314$, $p = 0.0066$). The Tukey HSD post-hoc test indicated significant differences in dam height between only one set of HU12s, Wittwer Canyon - Santa Clara River and Temple Fork ($p = 0.0141$; Figure 2.7). Additionally, ANOVA indicated differences in dam height between different dam construction materials ($f = 3.913$, $df = 316$, $p = 0.0002$), and the Tukey HSD post-hoc test showed differences in height between dams built from aspen and those built with willow (p = 0.0004), and also differences between aspen and grass (p = 0.0281) with aspen producing taller dams in each case (Figure 2.7).

Dam complex size ranged from 1 dam to 21 dams with a mean of 6.1 and standard deviation of 4.5. The number of dams per dam complex most closely followed a lognormal distribution with mean 1.55 and variance 0.72 (Figure 2.8).

Table 2.5. Summary of the total number of dams for which rapid field assessments were conducted by 12 digit hydrologic unit (HU12). H is the mean dam height for each HU12 and SD the standard deviation of dam height. The total number of dams is also broken down by dam type which includes primary (Prmy) and secondary (Secdry) dams, and dam condition which includes intact (Intact), breached (Brchd), and Blown-out (Blwn) dams.

HU 12 Name	**H (m)**	**SD (m)**	**Prmy Dams**	**Secdry Dams**	**Intact Dams**	**Brchd Dams**	**Blwn Dams**	**Total Dams**
Beaver Creek	0.91	0.21	13	49	28	26	8	62
Box Creek	0.77	0.23	4	17	8	8	5	21
Curtis Creek	0.94	0.37	4	33	14	19	4	37
Cutler Creek-North Fork Ogden River	0.88	0.28	8	78	30	1	55	86
Huff Creek	0.97	0.44	5	24	27	2	0	29
Lower Mink Creek	0.64	0.40	1	4	5	0	0	5
Pineview Reservoir-North Fork Ogden River	1.01	0.35	7	15	20	2	0	22
Rock Creek	0.92	0.28	9	93	77	23	2	102
South Fork Little Bear River	0.88	0.24	1	8	9	0	0	9
Temple Fork	1.08	0.52	22	95	96	15	6	117
Wittwer Canyon-Santa Clara River	0.58	0.19	1	9	8	1	1	10
Total	**-**	**-**	**75**	**425**	**322**	**97**	**81**	**500**
Average	**0.95**	**0.39**	**-**	**-**	**-**	**-**	**-**	**-**

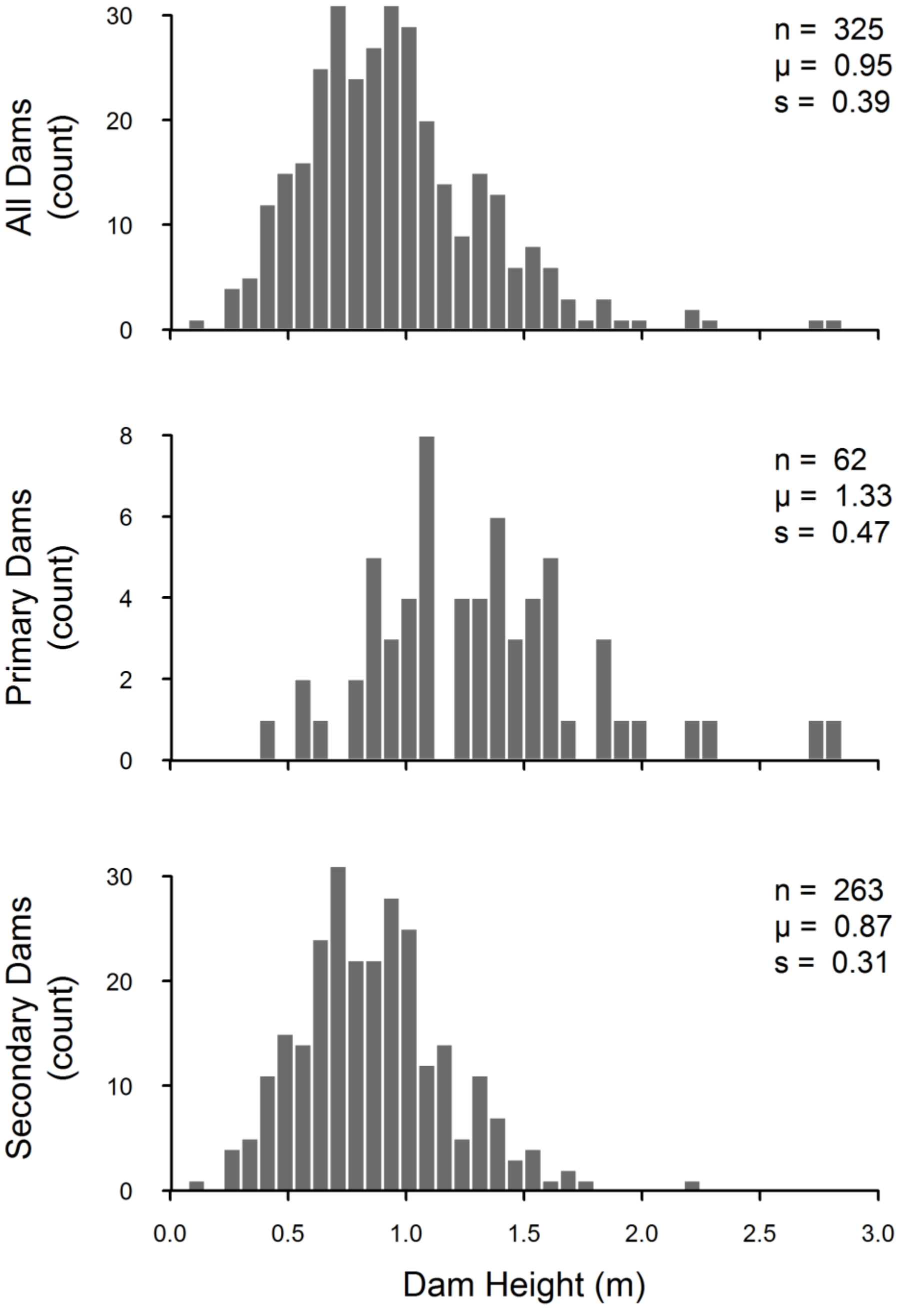


Figure 2.6. Dam height distributions of intact beaver dams for all dams, primary dams, and secondary dams.

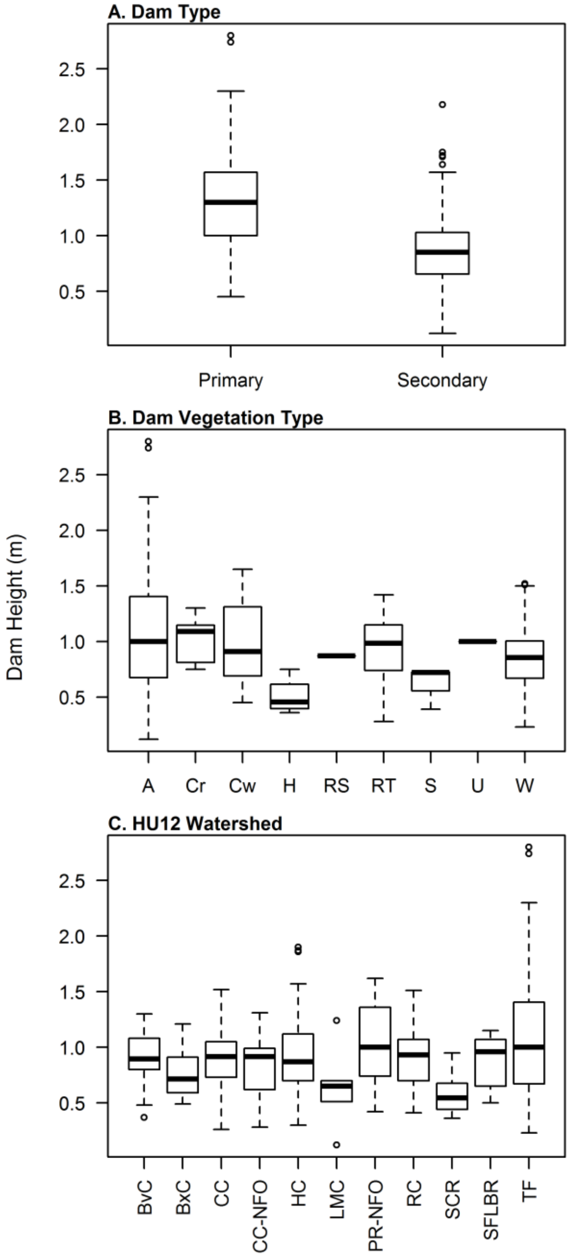


Figure 2.7. Dam height by dam type, primary construction material, and HU12 watershed. Vegetation types: A = aspen, Cr = conifer, Cw = cottonwood, H = herbaceous, RS = unidentified riparian shrub, RT = unidentified riparian tree, S = sagebrush, U = unknown, W = willow. HU12 watersheds: BvC = Beaver Creek, BxC = Box Creek, CC = Curtis Creek, CC-NFO = Cutler Creek North Fork Ogden River, HC = Huff Creek, LMC = Lower Mink Creek, PR-NFO = Pineview Reservoir North Fork Ogden River, RC = Rock Creek, SCR = Wittwer Canyon Santa Clara River, TF = Temple Fork.

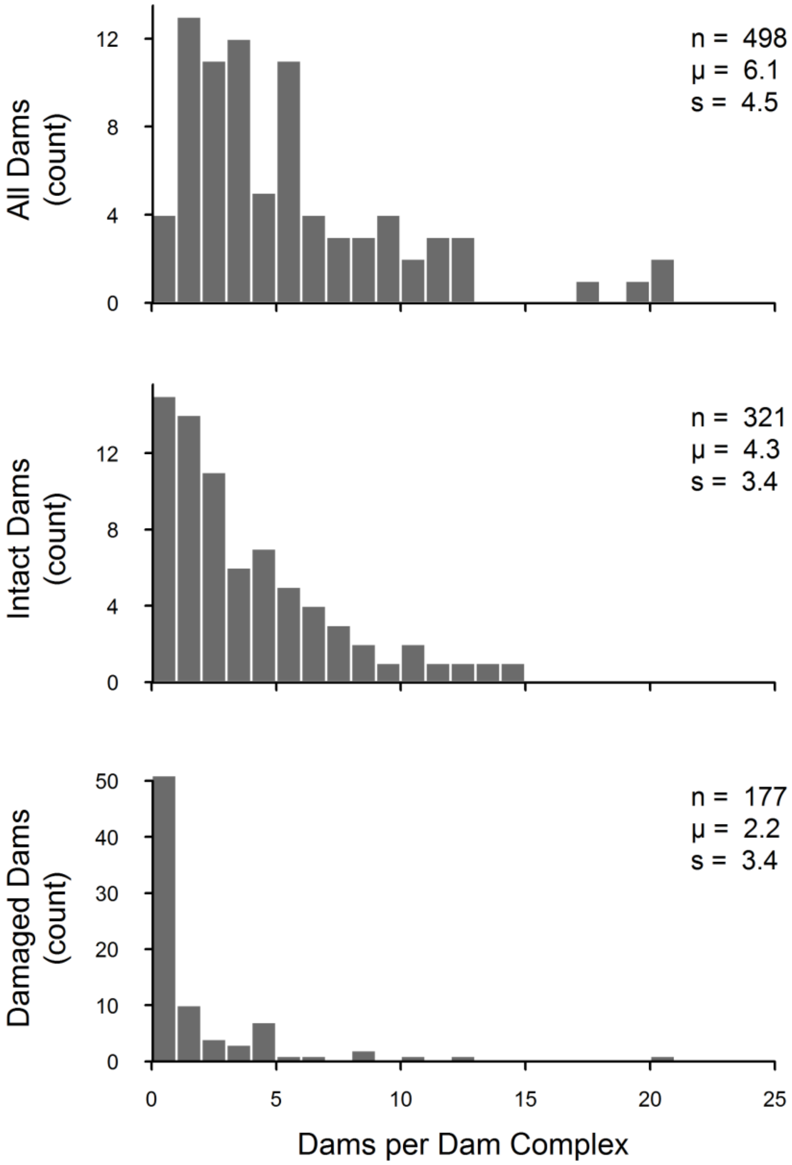


Figure 2.8. Number of dams per dam complex including all dams, intact dams, and damaged dams where damaged dams are the combination of breached and blown-out dams.

High-resolution Topography

From high-resolution topographic surveys crest lengths and heights were extracted for 61 beaver dams, actual pond areas and volumes for 35 dams, and maximum pond areas volumes for 56 dams (Table 2.5). The reach slope values extracted from 10 m

NED DEMs and used to fit the multiple regression model ranged from 0.0097 – 0.0788, dam heights ranged from 0.44 m – 1.85 m, and pond volumes from 3.34 m^3 – 314.36 m^3. The intercept of the fitted multiple regression model was 1.79 ($p = 0.0058$), the square root of dam height had a positive effect on pond volume ($\beta = 2.70$, SE = 0.64, $p = 0.0001$), and reach slope had a negative effect on pond volume ($\beta = -26.11$, SE = 3.86, $p < 0.0001$). Overall, the model explained 51.3% of variation in pond volume.

BD-SWEA Validation

Estimates of pond area from BD-SWEA were validated against the corresponding pond areas for 74 beaver dams and ponds from Temple Fork, and 34 from the North Fork of the Ogden River (n=108). When comparing the natural log of dam heights modeled with a 1 m LiDAR DEM to the natural log of observed dams heights, the intercept (2.05) and slope (0.41) of the regression line differed from zero and one ($p < 0.0001$) and the estimate for the slope of the regression line with the intercept held at zero was 0.85 which was also significantly different than one ($p < 0.0001$), and shows the model is underestimating observed areas (Figure 2.9A, D). Similarly, when the same regression is conducted using pond areas modeled with 10 m NED DEMs estimates of intercept (1.28)

Table 2.6. Summary of dam heights, crest lengths, pond areas, and pond volumes extracted from high-resolution topographic surveys of beaver dams and ponds, where n equals the number of observations for each variable, and SD the standard deviation.

Variable	**n**	**SD**	**Mean**	**Min**	**Max**
Dam Height (m)	61	0.31	0.97	0.44	1.85
Crest Length (m)	61	9.02	11.12	2.65	62.08
Actual Area (m^2)	35	119.01	151.72	24.08	531.13
Maximum Area (m^2)	56	160.78	172.69	20.41	857.29
Actual volume (m^3)	35	37.84	43.48	3.90	180.36
Maximum Volume (m^3)	56	57.44	54.63	3.34	314.36

and slope (0.17) simultaneously differ from zero and one ($p < 0.0001$), and with an intercept of zero the estimated slope (0.45) remains less than one ($p < 0.0001$), suggesting the 10 m data also underestimates pond size (Figure 2.9B, E). When increasing the spatial scale of validation to the entire Little Bear – Logan River watershed, and using observed and modeled pond areas of the 1211 beaver ponds summed by HU12 (n=21), the intercept (-1.63) and slope (1.16) of the regression analysis did not differ significantly from zero and one ($p = 0.2155$), and with the intercept held at zero the slope estimate of 1.09 was also not significantly different than one ($p = 0.9990$; Figure 2.9C, F).

Regression of maximum pond volumes extracted from high-resolution DEMs at Bridge Creek (n = 32), Curtis Creek (n = 8), and Temple Fork (n =16) against pond volumes modeled from BD-SWEA with 1m LiDAR (Bridge Creek and Temple Fork; n = 48) and 10 m NED (all sites; n = 56) DEMs yielded the following results. For the 1 m LiDAR data, linear regression estimated an intercept of 0.32 and slope of 0.92, which were not significantly different than zero and one ($p = 0.85$; Figure 2.10A, C). For the 10 m data, the estimated intercept was 0.21 and slope 0.97 and were not significantly different than zero and one ($p = 0.7951$; Figure 2.10B, D). Regressions for pond volumes modeled from BD-SWE with 1 m and 10 m DEMs accounted for 42% and 43% of variation in pond volume, respectively.

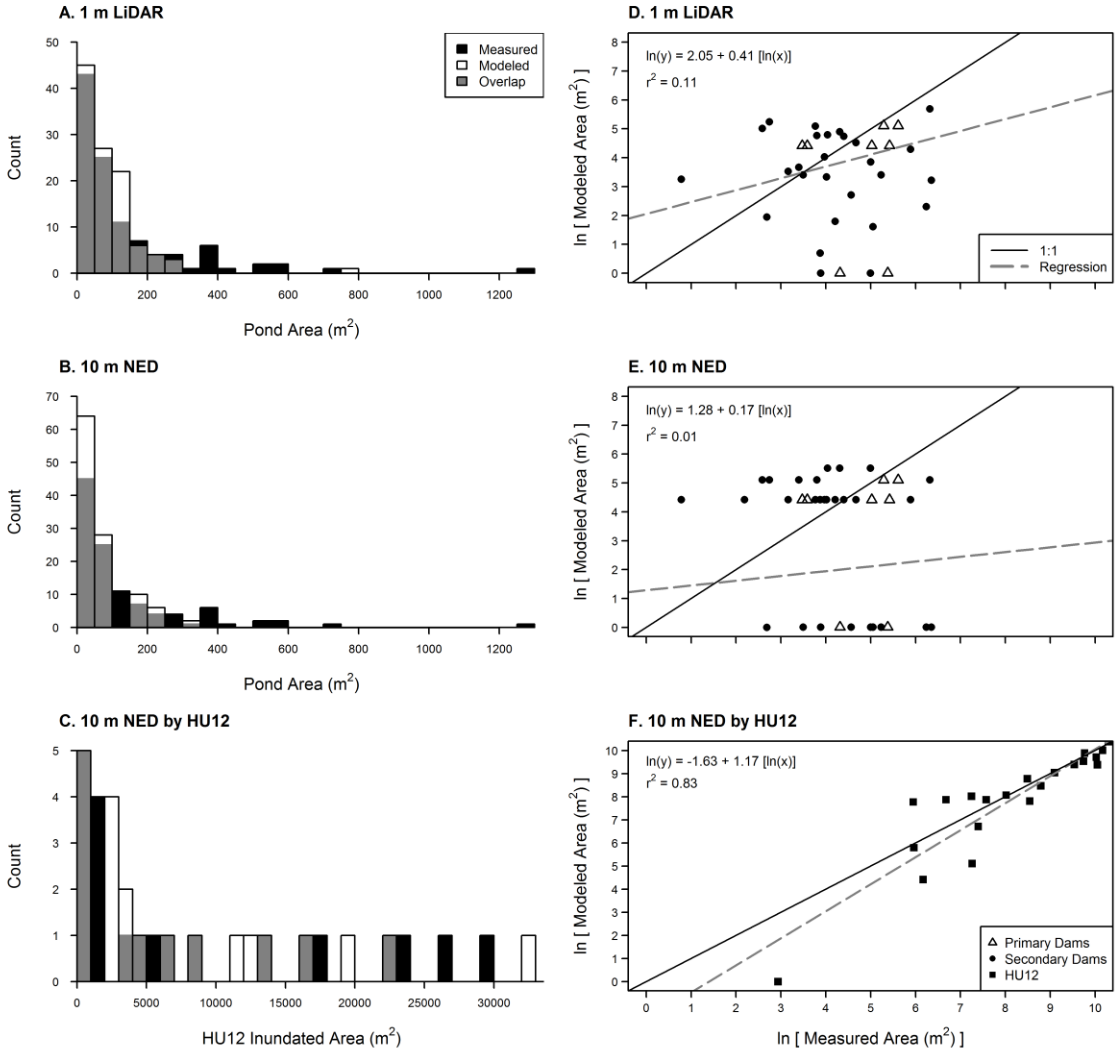


Figure 2.9. Linear regression validation (D, E, F) of BD-SWEA pond area estimates modeled with 1 m (A, D) and 10 m (B, C, E, F) DEM inputs, and comparison of distributions of modeled and measured pond areas (A, B, C). Measured areas were collected in the field with an iPad GPS (A, B), or by digitizing ponds from aerial imagery (C). Part C shows the digitized pond area summed by HU12 for the Little Bear – Logan River HU8. The linear arrangements of points in (B) are a result of cell resolution, as the smallest possible area of a modeled pond when using a 10 m DEM is 100 m^2.

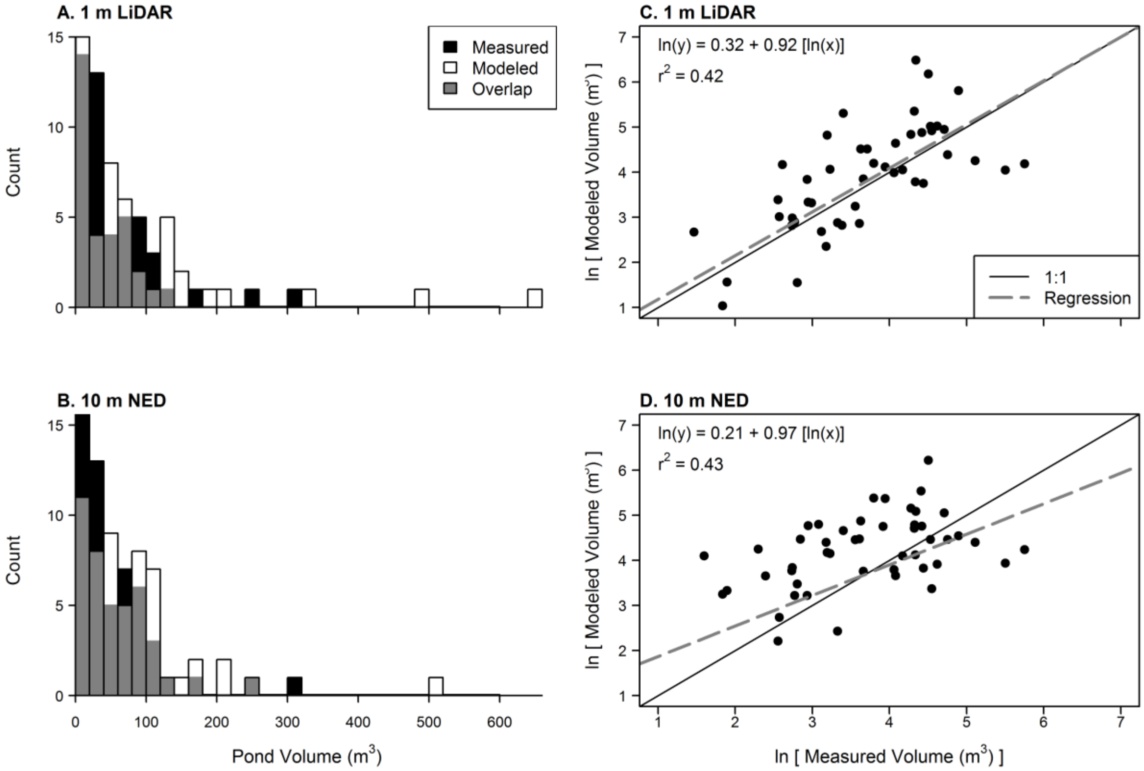


Figure 2.10. Linear regression validation and distributions of measured pond volumes and pond volumes modeled with BD-SWEA using 1 m (A, C) and 10 m (B, D) DEM inputs. Measured values were obtained from high-resolution DEMs resulting from surveys of beaver ponds at Bridge Creek, OR, Spawn Creek, UT, and Curtis Creek, UT.

Table 2.7. Mean and standard deviation values for observed (Obs.) and modeled (Mod.) areas and volumes of beaver ponds. Values we measured from high resolution topography (HRT), field surveys, and aerial imagery and modeled with the Beaver Dam Surface Water Estimation Algorithm using DEMs of 1 m and 10 m resolution.

Data source	**Value type**	**DEM resolution**	**n**	**Obs. mean**	**Obs. SD**	**Mod. mean**	**Mod. SD**
HRT	Volume	1 m	48	57.31	60.45	87.19	121.80
HRT	Volume	10 m	56	54.63	57.44	76.97	82.27
Field survey	Area	1 m	108	135.44	181.76	84.36	95.11
Field survey	Area	10 m	108	135.44	181.76	55.04	80.00
Aerial imagery	Area	10 m	1211	154.66	207.25	137.10	139.27

DISCUSSION

We observed significant differences in height between primary and secondary beaver dams with secondary dams being nearly one half meter taller on average, and also observed that secondary dams were six times more prevalent than primary dams. Thus, the size of primary dams may make the magnitude of their individual impacts larger, but the greater number of secondary dams could lead to greater cumulative impacts potentially creating an interesting mosaic of physical and ecologic changes between the two dam types. These results also indicate that when modeling areas and volumes of ponds, or considering the potential impacts of dams, at landscape scales the differences in size and frequency of occurrence for each dam type may be an important factor to consider. Overall, our observations of dam height are generally comparable to mean dam heights and dam height ranges observed by others (Table 2.1).

Dam heights appear to exhibit little variation across hydrologic units. Our ability to detect these differences may have been limited by small sample sizes in some watersheds and large sample sizes in others. Additionally, it is unclear if the observed differences in dam heights between watersheds are a function of differences across space, vegetation, physiographic setting, or beaver behavior. The two HU12s with a significant difference in dam height were Temple Fork (larger dams) and Wittwer Canyon – Santa Clara River (smaller dams). However, there was also a significant difference observed between the height of dams constructed with aspen (majority in Temple Fork) and grass/reeds (majority on Santa Clara River), so in this case it is unclear if dam height differences result from construction material, location, or a combination of both factors. The greater number of primary dams in Temple Fork may also contribute to the difference in dam height. We also report significant differences between the height of dams constructed with willow and those constructed with aspen, and also dams built with grass and compared to those built with aspen, aspen producing the larger dams in each case. It is unclear if these effects are a direct result of vegetation type, or if there may be an additional factor such as stream slope playing a role. In our study areas aspen are generally most prevalent high in the watershed where stream slopes are steeper. On these steeper gradients a taller dam must be built to inundate the same area that a shorter dam could accomplish on a lower gradient reach.

Perhaps our most salient results come from validation of BD-SWEA. While the algorithm's ability to accurately predict the area of individual ponds may be suspect, the general pattern of prediction was consistent with observed values at landscape scales using nationally available 10 m topographic data. The ability of BD-SWEA to predict pond area is in part related to the scale of the input data. With a 10 m input the smallest size a modeled beaver pond can be is 100 m^2, resulting in consistent over- or under-estimation of observed beaver pond areas when observed pond sizes are between 0 and 100 m^2 (Figure 2.9). This is apparent in Figure 2.9D where linear patterns are present in the scatter plot. These patterns result from the resolution of the input DEM as the smallest area that can be modeled on a 10 m grid is 100 m^2 and many of the observed ponds had areas smaller than this value. This pattern may also be a reflection of the dam height adjustment algorithm within BD-SWEA. In settings that are relatively steep, or relatively flat, the modeled dam height may not be tall enough to inundate surrounding cells and as the height of dam is iteratively increased by 0.1 m the estimated pond volume may increase too greatly and fall outside of the regression prediction intervals, defaulting to the original settings. Additionally, the dam to be modeled may be placed at an inopportune location, such as a sink in the DEM, and require substantial increases in dam height for modeled inundation to occur. One potential solution to address small pond sizes in relatively steep environments would be to use a sink-filled DEM. However, this method may result in overestimation of pond size in flatter environments where subtle sinks may constrain pond area. At the scale of HU12 watersheds these inconsistencies are somewhat muted as BD-SWEA did relatively well modeling the overall area of the landscape inundated by beaver dams (Figure 9C, F).

Fortunately, BD-SWEA provided much more accurate estimations for volume predictions for both 1 m and 10 m DEMs (Figure 2.10). These results suggest that estimation of pond volumes is much more robust to input spatial data resolution than estimation of pond areas. We expect that BD-SWEA would not produce reliable results with input data of resolutions coarser than 10 m, simply because the ability of the model to capture smaller pond sizes would be severely limited, and evidence of this effect is already seen at 10 m resolution. Estimated vertical error of the NED 10 m DEMs is 2 m and may be as high as 5 m in forested areas (Gesch *et al.*, 2002). While these error magnitudes are great to enough to offset any estimated changes to beaver pond depths, validating our model against 1 m observed pond areas and volumes, and modeling with both 1 m and 10 m DEMs indicates that the inundation signal of beaver ponds is detectable with the 10 m NED DEMs.

In the interest of sample size and time, we did not collect dam crest length or pond depth during our rapid field assessments. These variables have been important in others' attempts to quantify the size of beaver ponds (Beedle, 1991; Karran *et al.*, 2016), and it is possible that the performance of BD-SWEA could be improved by including additional parametrizations for these variables. Volume estimates may be more accurate with inclusion of a variable describing maximum pond depth, or pond age, as beaver ponds tend to aggrade sediment and become shallower as they get older, especially if beaver stop maintaining the dam. Estimates may be further improved with inclusion of a variable describing dam crest length (Beedle, 1991; Karran *et al.*, 2016), but at a spatial resolution of 10 m, dam crest lengths may not be accurately represented. Implementation of additional variables may be more advantageous when modeling with higher resolution datasets when the more detailed resolution may allow for differentiation of small-scale features. Currently, the simplicity of BD-SWEA, requiring only topography and dam height estimates for parameterization, presents opportunities to apply the algorithm at large spatial scales.

Overall, BD-SWEA presents a tractable, predictive method for evaluating the potential influence of beaver dam building on surface water extent and volume. As the effects of beaver dams on surface water have ecological and hydrological benefits on many landscapes (Hood and Bayley, 2008; Johnston and Naiman, 1990b) a predictive method provides opportunities to assess how, and where, beaver restoration may produce desired results, or potential problems. Intentionally, BD-SWEA leverages nationally available datasets which preform adequately, and more precise results are attainable where higher quality data exist. We see results from BD-SWEA as encouraging as they open the door to project the potential hydrologic impacts of beaver dams in a spatially-explicit manner using data that are widely available. Additionally, when coupled with a spatially-explicit dam capacity model, BD-SWEA provides a tool to identify potential impacts before initiating restoration efforts, and could also be a useful tool to evaluate the effect increasing beaver dams may have on buffering potential shifts in hydrologic regimes stimulated by climate change.

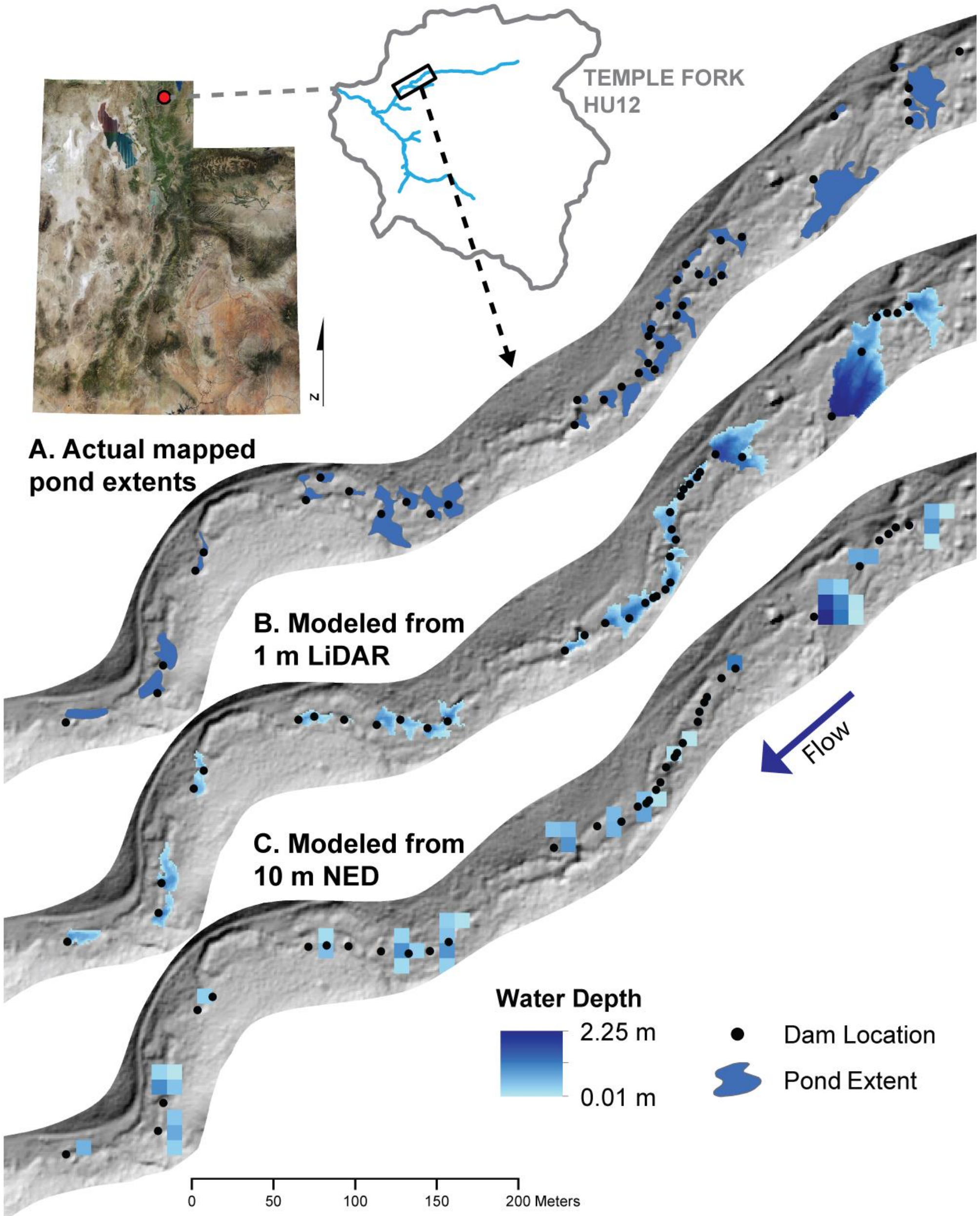


Figure 2.11. Dam locations and extents for data collected in the field with an iPad and GPS (A), modeled pond extents and depths using BD-SWEA with a 1 m LiDAR DEM input (B), and modeled pond extents and depths using BD-SWEA with a 10 m NED DEM input (C), for a stream reach in the Temple Fork HU12. A hillshade derived from

the 1 m LiDAR DEM is shown for context and outputs are clipped to the valley-bottom extent.

REFERENCES

Aleksiuk, M., 1968. Scent-Mound Communication, Territoriality, and Population Regulation in Beaver (Castor Canadensis Kuhl). Journal of Mammalogy 49:759–762.

Barnes, W.J. and E. Dibble, 1988. The Effects of Beaver in Riverbank Forest Succession. Canadian Journal of Botany 66:40–44.

Beedle, D.L., 1991. Physical Dimensions and Hydrologic Effects of Beaver Ponds on Kuiu Island in Southeast Alaska., http://ir.library.oregonstate.edu/xmlui/handle/1957/9343, *accessed* 1 Feb 2016.

Bouwes, N., N. Weber, C.E. Jordan, W.C. Saunders, I.A. Tattam, C. Volk, J.M. Wheaton, and M.M. Pollock, 2016. Ecosystem Experiment Reveals Benefits of Natural and Simulated Beaver Dams to a Threatened Population of Steelhead (Oncorhynchus Mykiss). Scientific Reports 6:28581, doi: 10.1038/srep28581.

Bryant, M.D., 1983. The Role of Beaver Dams as Coho Salmon Habitat in Southeast Alaska Streams. Proceedings of the Olympic Wild Fish Conference. Peninsula College, Port Angeles, Washington, pp. 183–192.

Burchsted, D., M. Daniels, R. Thorson, and J. Vokoun, 2010. The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters. BioScience 60:908–922, doi: 10.1525/bio.2010.60.11.7.

Camp, R.J. and J.M. Wheaton, 2014. Streamlining Field Data Collection with Mobile Apps. EOS, Transactions American Geophysical Union 95:453–454.

Collen, P. and R.J. Gibson, 2000. The General Ecology of Beavers (Castor Spp.), as Related to Their Influence on Stream Ecosystems and Riparian Habitats, and the Subsequent Effects on Fish - A Review. Reviews in Fish Biology and Fisheries 10:439–461, doi: 10.1023/A:1012262217012.

Cooke, H.A. and S. Zack, 2008. Influence of Beaver Dam Density on Riparian Areas and Riparian Birds in Shrubsteppe of Wyoming. Western North American Naturalist 68:365–373, doi: 10.3398/1527-0904(2008)68[365:IOBDDO]2.0.CO;2.

Dugmore, A.R., 1914. The Romance of the Beaver: Being the History of the Beaver in the Western Hemisphere. Heinemann.

Feiner, K. and C.S. Lowry, 2015. Simulating the Effects of a Beaver Dam on Regional Groundwater Flow through a Wetland. Journal of Hydrology: Regional Studies 4:675–685.

GDAL Development Team, 2014. GDAL - Geospatial Data Abstraction Library, Version 1.11., http://gdal.osgeo.org, *accessed* 3 Jan 2017.

Gesch, D., M. Oimoen, S. Greenlee, C. Nelson, M. Steuck, and D. Tyler, 2002. The National Elevation Dataset. Photogrammetric Engineering and Remote Sensing 68:5–32.

Grasse, J.E. and E.F. Putnam, 1955. Beaver Management and Ecology in Wyoming. Wyoming Game and Fish Commission.

Gurnell, A.M., 1998. The Hydrogeomorphological Effects of Beaver Dam-Building Activity. Progress in Physical Geography 22:167–189, doi: 10.1177/030913339802200202.

Hood, G.A. and S.E. Bayley, 2008. Beaver (Castor Canadensis) Mitigate the Effects of Climate on the Area of Open Water in Boreal Wetlands in Western Canada. Biological Conservation 141:556–567, doi: 10.1016/j.biocon.2007.12.003.

Hood, G.A. and D.G. Larson, 2015. Ecological Engineering and Aquatic Connectivity: A New Perspective from Beaver-Modified Wetlands. Freshwater Biology 60:198–208, doi: 10.1111/fwb.12487.

Ives, R.L., 1942. The Beaver-Meadow Complex. Journal of Geomorphology 5:191–203.

Johnston, C.A. and R.J. Naiman, 1987. Boundary Dynamics at the Aquatic-Terrestrial Interface: The Influence of Beaver and Geomorphology. Landscape Ecology 1:47–57, doi: 10.1007/BF02275265.

Johnston, C.A. and R.J. Naiman, 1990a. Aquatic Patch Creation in Relation to Beaver Population Trends. Ecology:1617–1621, http://www.jstor.org/stable/1938297, *accessed* 7 Mar 2014.

Johnston, C.A. and R.J. Naiman, 1990b. The Use of a Geographic Information System to Analyze Long-Term Landscape Alteration by Beaver. Landscape Ecology 4:5–19.

Johnston, Naiman, C.A. Johnston, and R.J. Naiman, 1990. The Use of a Geographic Information System to Analyze Long-Term Landscape Alteration by Beaver. Landscape Ecology 4:5–19.

Karran, D.J., C.J. Westbrook, J.M. Wheaton, C.A. Johnston, and A. Bedard-Haughn, 2016. Rapid Surface Water Volume Estimations in Beaver Ponds. Hydrology and Earth System Sciences Discussions, doi: 10.5194/hess-2016-352.

Levine, R. and G.A. Meyer, 2014. Beaver Dams and Channel Sediment Dynamics on Odell Creek, Centennial Valley, Montana, USA. Geomorphology 205:51–64, doi: 10.1016/j.geomorph.2013.04.035.

Lokteff, R.L., B.B. Roper, and J.M. Wheaton, 2013. Do Beaver Dams Impede the Movement of Trout? Transactions of the American Fisheries Society 142:1114–1125, doi: 10.1080/00028487.2013.797497.

Lowry, M.M., 1993. Groundwater Elevations and Temperature Adjacent to a Beaver Pond in Central Oregon. Oregon State University, http://ir.library.oregonstate.edu/jspui/handle/1957/9566, *accessed* 18 Dec 2013.

Macfarlane, W.W., J.M. Wheaton, N. Bouwes, M.L. Jensen, J.T. Gilbert, N. Hough-Snee, and J.A. Shivik, 2017. Modeling the Capacity of Riverscapes to Support Beaver Dams. Geomorphology 277:72–99.

Majerova, M., B.T. Neilson, N.M. Schmadel, J.M. Wheaton, and C.J. Snow, 2015. Impacts of Beaver Dams on Hydrologic and Temperature Regimes in a Mountain Stream. Hydrology and Earth System Sciences 19:3541–3556, doi: 10.5194/hess-19-3541-2015.

McComb, W.C., J.R. Sedell, and T.D. Buchholz, 1990. Dam-Site Selection by Beavers in an Eastern Oregon Basin. Great Basin Naturalist 50:273–281.

Meentemeyer, R.K. and D.R. Butler, 1999. Hydrogeomorphic Effects of Beaver Dams in Glacier National Park, Montana. Physical Geography 20:436–446, doi: 10.1080/02723646.1999.10642688.

Morgan, L.H., 1868. The American Beaver and His Works. J. B. Leppincott and Company, Philadephia.

Muller-Schwarze, D., 2011. The Beaver: Its Life and Impact. Cornell University Press.

Müller-Schwarze, D. and S. Heckman, 1980. The Social Role of Scent Marking in Beaver (Castor Canadensis). Journal of Chemical Ecology 6:81–95.

Naiman, R.J., C.A. Johnston, and J.C. Kelley, 1988. Alteration of North American Streams by Beaver. Bioscience 38:753–762, http://www.jstor.org/stable/pdfplus/1310784.pdf?acceptTC=true&acceptTC=true&jpdConfirm=true, *accessed* 18 Dec 2013.

NCALM, 2011. Extending Predictions of Bonneville Cutthroat Trout Spawning Hotspots Using Multi-Scalar LiDAR: SEED Project., doi: 10.5069/G9HQ3WTG.

Nobre, A.D., L.A. Cuartas, M. Hodnett, C.D. Rennó, G. Rodrigues, A. Silveira, M. Waterloo, and S. Saleska, 2011. Height Above the Nearest Drainage – a

Hydrologically Relevant New Terrain Model. Journal of Hydrology 404:13–29, doi: 10.1016/j.jhydrol.2011.03.051.

Nyssen, J., J. Pontzeele, and P. Billi, 2011. Effect of Beaver Dams on the Hydrology of Small Mountain Streams: Example from the Chevral in the Ourthe Orientale Basin, Ardennes, Belgium. Journal of Hydrology 402:92–102, doi: 10.1016/j.jhydrol.2011.03.008.

Pollock, M.M., T.J. Beechie, J.M. Wheaton, C.E. Jordan, N. Bouwes, N. Weber, and C. Volk, 2014. Using Beaver Dams to Restore Incised Stream Ecosystems. BioScience 64:279–290, doi: 10.1093/biosci/biu036.

Pollock, M.M., G. Lewallen, K. Woodruff, C.E. Jordan, and J.M. Castro, 2015. The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains.

Pollock, M.M., J.M. Wheaton, N. Bouwes, and C.E. Jordan, 2011. Working with Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed.

Portugal, E., J.M. Wheaton, and N. Bouwes, 2015a. Spring Creek Area Adaptive Beaver Management Plan. :25, doi: 10.13140/RG.2.1.2075.3361.

Portugal, E., J.M. Wheaton, K. Sorenson, M. Majerova, B. Hunt, and N. Bouwes, 2015b. Hardware Ranch Adaptive Beaver Management Plan. :26, https://www.researchgate.net/profile/Joseph_Wheaton/publication/309905727_Draft_-_Hardware_Ranch_Adaptive_Beaver_Management_Plan/links/5825ece808ae61258e4616f7.pdf, *accessed* 5 Apr 2017.

Puttock, A., A.M. Cunliffe, K. Anderson, and R.E. Brazier, 2015. Aerial Photography Collected with a Multirotor Drone Reveals Impact of Eurasian Beaver Reintroduction on Ecosystem Structure. Journal of Unmanned Vehicle Systems.

Puttock, A., H.A. Graham, A.M. Cunliffe, M. Elliott, and R.E. Brazier, 2017. Eurasian Beaver Activity Increases Water Storage, Attenuates Flow and Mitigates Diffuse Pollution from Intensively-Managed Grasslands. Science of The Total Environment 576:430–443.

Rennó, C.D., A.D. Nobre, L.A. Cuartas, J.V. Soares, M.G. Hodnett, J. Tomasella, and M.J. Waterloo, 2008. HAND, a New Terrain Descriptor Using SRTM-DEM: Mapping Terra-Firme Rainforest Environments in Amazonia. Remote Sensing of Environment 112:3469–3481, doi: 10.1016/j.rse.2008.03.018.

Rosell, F., O. Bozsér, P. Collen, and H. Parker, 2005. Ecological Impact of Beavers Castor Fiber and Castor Canadensis and Their Ability to Modify Ecosystems. Mammal Review 35:248–276, doi: 10.1111/j.1365-2907.2005.00067.x.

Runyon, M.J., D.B. Tyers, B.F. Sowell, and C.N. Gower, 2014. Aspen Restoration Using Beaver on the Northern Yellowstone Winter Range under Reduced Ungulate Herbivory. Restoration Ecology 22:555–561.

Scheffer, P.M., 1938. The Beaver as an Upstream Engineer. Soil Conservation 3:178–181.

Smith, A.E., 1950. Effects of Water Run-off and Gradient on Beaver in Mountain Streams. University of Michigan, Ann Arbor, Michigan.

Stout, T.L., M. Majerova, and B.T. Neilson, 2016. Impacts of Beaver Dams on Channel Hydraulics and Substrate Characteristics in a Mountain Stream. Ecohydrology.

Townsend, J.E., 1953. Beaver Ecology in Western Montana with Special Reference to Movements. Journal of Mammalogy 34:459–479.

UDWR, 2010. Utah Beaver Management Plan 2010-2020. Salt Lake City, UT.

Utah State University LASSI Service Center, 2012. Great Salt Lake Wetlands 2012 LiDAR Mapping Project: Box Elder, Weber, Davis, Salt Lake and Tooele Counties, Utah., http://files.geology.utah.gov/databases/lidar/pdf/GSL_Report.pdf, *accessed* 5 Apr 2017.

Westbrook, C.J., D.J. Cooper, and B.W. Baker, 2006. Beaver Dams and Overbank Floods Influence Groundwater-Surface Water Interactions of a Rocky Mountain Riparian Area. Water Resources Research 42:1–12, doi: 10.1029/2005WR004560.

Wolf, E.C., D.J. Cooper, and N.T. Hobbs, 2007. Hydrologic Regime and Herbivory Stabilize an Alternative State in Yellowstone National Park. Ecological Applications 17:1572–1587, http://www.esajournals.org/doi/abs/10.1890/06-2042.1, *accessed* 18 Dec 2013.

Woo, M.-K. and J.M. Waddington, 1990. Effects of Beaver Dams on Subarctic Wetland Hydrology. Arctic 43:223–230, doi: 10.14430/arctic1615.

Woolpert Inc., 2012. Bridge Creek LiDAR: Technical Data Report., https://coast.noaa.gov/htdata/raster2/imagery/BridgeCreekOR_2013_2494/Bridge_Creek_LiDAR.pdf, *accessed* 5 Apr 2017.

CHAPTER 3

TO WHAT DEGREE COULD BEAVER DAMS BUFFER A DECLINING SNOWPACK?

ABSTRACT

Dam building activity by North American Beaver (*Castor canadensis*) changes the timing of stream water delivery and facilitates groundwater infiltration, overall increasing natural water storage behind and adjacent to dams. At the stream reach scale, increased water storage often alters hydrologic regimes by attenuating annual, and storm-event hydrographs, and increasing base flows. In light of predicted snowpack decreases and increased variability in precipitation regimes for the western United States, the volume of high-elevation water storage (i.e. snowpack) is expected to decrease, having profound impacts on hydrologic regimes. Water storage resulting from increased beaver dam construction may potentially buffer some of the hydrologic effects associated with declining snowpack. We apply the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA) to estimate potential surface water storage and parameterize a groundwater model (MODFLOW) to estimate resulting groundwater storage increases for the entire Bear River basin under four different beaver dam capacity scenarios. Estimated increases to water storage resulting from beaver presented in the context of expected reductions in average annual maximum snow water equivalent under warming scenarios of 1˚C, 2 ˚C, 3 ˚C, and 4 ˚C, and existing and proposed reservoir storage within the basin. While the water storage provided by beaver dams is only a small fraction of expected snow water equivalent loss, accounting for a maximum of 3% of snow water equivalent loss in a watershed, it is not insubstantial and may prove beneficial for ecosystems at higher

elevations where human-made reservoirs are not available to regulate hydrologic regimes. When considering snow water equivalent loss within valley-bottoms, beaver dams in many watersheds may account for more than 50% of estimated losses. These results stress the importance of further research examining how the cumulative effects of dams may affect the timing of runoff under changing precipitation regimes.

INTRODUCTION

Beaver dams diversify residence times and complicate flow paths of water in lotic environments by direct ponding, diverting flow onto floodplains, increasing groundwater infiltration, and altering evapotranspiration rates (Lowry, 1993; Westbrook *et al.*, 2006; Woo and Waddington, 1990). For steam reaches where beaver dams are present, the cumulative results of these effects tend to attenuate flood peaks and increase base flow, generally stabilizing local flow regimes (Majerova *et al.*, 2015; Nyssen *et al.*, 2011; Puttock *et al.*, 2017). These hydrologic alterations facilitated by beaver dam building activity contrast directly with observed and predicted runoff shifts in snow dominated regions of the western United States. Widespread changes to precipitation and temperature patterns (Klos *et al.*, 2014; Tennant *et al.*, 2015a) are contributing to earlier spring runoff, decreased base flows, and greater variability in flow magnitude (Barnett *et al.*, 2005; Stewart *et al.*, 2004, 2005). Under most likely warming projections, snowpack will continue to decline. A diminished snowpack decreases the natural storage that buffers extreme events and stabilizes hydrographs (Barnett *et al.*, 2005). As beaver dams are most frequent on lower order tributaries that occur higher in watersheds (Johnston and Naiman, 1990a; Naiman *et al.*, 1988; Rosell *et al.*, 2005), increasing the number of these dams may provide an alternative source of water storage to buffer hydrologic changes, thus mitigating some of the hydrologic uncertainty resulting from snowpack decreases (Gibson and Olden, 2014; Nyssen *et al.*, 2011).

The ability of beaver dams to alter hydrology (at least within the reaches they occupy) is largely driven by the additional water storage they create by impounding streamflow and increasing infiltration to raise local groundwater levels (Figure 3.1). Surface volumes of beaver ponds exhibit large variation with reported values ranging from 1 m^3 to 12,000 m^3 (Beedle, 1991; Karran *et al.*, 2016). Following introduction of beaver to the to the Ourthe Orientale sub-basin of Belgium, Nyssen et al. (2011) observed an overall smoothening of the hydrograph, with general decreases in the magnitude of flood peaks and general increases to base flows which were positively correlated with beaver pond volume. Though they do not explicitly report pond volumes, Majerova et al. (2015) also recorded increased base flows after beaver occupied their study reach in northern Utah. As pond area is strong predictor of pond volume (Beedle, 1991; Karran *et al.*, 2016), others have leveraged aerial imagery to assess the hydrologic impacts of beaver by identifying areas inundated by beaver ponds (Hood and Bayley, 2008; Johnston *et al.*, 1990; Puttock *et al.*, 2015). Most notably, Hood and Bayley (2008) found that over a 54 year period fluctuation in the area of a landscape inundated by ponds was best predicted by the number of beaver lodges, as opposed to climatic variables.

Though beaver's impacts are most noticeable on the land surface, their effects on groundwater tables may be more significant hydrologically. Lowry (1993) indicated beaver dams may influence groundwater levels across the entire width of a valley bottom and documented lateral rises in groundwater tables as far as 50 m from a beaver pond with a corresponding increase to stream stage. Though the majority of groundwater change may be restricted to areas immediately around the pond, Westbrook et al. (2006) found that flows diverted onto the floodplain by a beaver dam raised water tables 600 m downstream of the dam's location. Feiner and Lowry (2015) simulated a 90% increase in groundwater discharge after construction of a beaver dam increased the size of a New York wetland. While these studies are relatively small in spatial extent, they illustrate the potential for beaver dams to profoundly increase shallow groundwater storage, and the role these groundwater stores may play in attenuating flood peaks and increasing base flows. However, because groundwater measurement typically requires intensive use of equipment, studies are generally limited to small spatial extents (Nobre *et al.*, 2011).

In several instances, local flood attenuation and increased base flows resulting from beaver dams have led researchers and managers to suggest beaver as means for restoring and conserving ecological systems in the face of climatic uncertainty (Cross *et al.*, 2012; Gibson and Olden, 2014; Popescu and Gibbs, 2009; Stevens *et al.*, 2007). There are at least three reasons why such a hypothesis may be plausible. First, in recent decades, beaver populations have rebounded in many areas of the United States and now occupy the entire extent of their former range (Pollock *et al.*, 2004), with densities in some localities approaching 50 dams per kilometer (Cooke and Zack, 2008; Gurnell, 1998; Macfarlane *et al.*, 2014; Rosell *et al.*, 2005). Secondly, despite this rebound from heavy extirpation during European settlement of North America, in most areas beaver still only occur at a fraction of their historical abundance (Dolan, 2010) leaving ample opportunity for expansion of existing colonies and reintroduction of beaver to historic habitats where they are not currently present (Fredlake, 1997; Macfarlane *et al.*, 2017).

Third, many of the areas with historically high densities of dams are located in low-order and headwater perennial streams (Collen and Gibson, 2000; Naiman *et al.*, 1988; Stevens *et al.*, 2007). Recent development of the Beaver Restoration Assessment Tool (BRAT), a beaver dam capacity model (Macfarlane *et al.*, 2017), and the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA, Chapter 2 herein), provide tractable means to assess the potential hydrologic impacts of beaver dams at large spatial scales across different physiographic settings.

Beaver dams and their effects have been widely studied. However, these studies have primarily quantified the impacts of existing beaver dams and beaver complexes at the spatial scale of stream reaches (~1 km). The limited (but growing) geographic range of studies documenting these hydrologic responses leaves a disparity in our knowledge of the way hydrologic impacts may transpire across broad spatial scales and diverse physiographic settings (Gibson and Olden, 2014). While reliable methods have been developed to estimate beaver pond volumes (i.e. surface water storage), such methods generally require *a priori* information about a beaver pond and are thus not suited for predictive estimation. Additionally, such surface volume estimations neglect potential changes to groundwater storage which can be significant (Feiner and Lowry, 2015; Lowry, 1993; Westbrook *et al.*, 2006). In part, broad scale estimation of beaver dam impacts on hydrology has been precluded by lack of spatially predictive beaver dam capacity and beaver pond inundation models. Recent development of such models now provides a means to extend our current knowledge to broader scales.

Much work has been conducted to identify local hydrologic effects of beaver dams and the mechanisms driving these effects. Indeed, beaver dams are capable of significantly altering stream hydrology, and may have advantages over human-made water storage reservoirs as they are highly dispersed and hold water higher in watersheds, similar to the function provided by natural snowpack water storage. These results raise the questions, to what degree could beaver dams alter hydrology at a scale meaningful to water resources management? Could increasing the number beaver dams buffer some of the hydrological effects associated with declining snowpack? We hypothesize that water storage provided by increasing the number beaver dams within riverscapes will alter hydrology over large spatial extents. Specifically, we postulate that the degree to which beaver dams may buffer snowpack declines will be proportional to the amount of additional water storage beaver dams provide. We attempt to test these hypotheses by quantifying the volume of water that could be stored in beaver dams in comparison to expected losses from snowpack. We implement the BRAT beaver dam capacity model (Macfarlane *et al.*, 2017), BD-SWEA (Hafen, Chapter 2 herein), and a groundwater model (MODFLOW; Harbaugh, 2005) to quantify potential water storage increases under different dam capacity scenarios, and the Tennant et al. (2015) framework to estimate losses in snow water equivalent (SWE) under different temperature warming scenarios. Our results provide a first assessment of the degree to which beaver may buffer the effects of declining snowpack in snow-dominated regions of western North America.

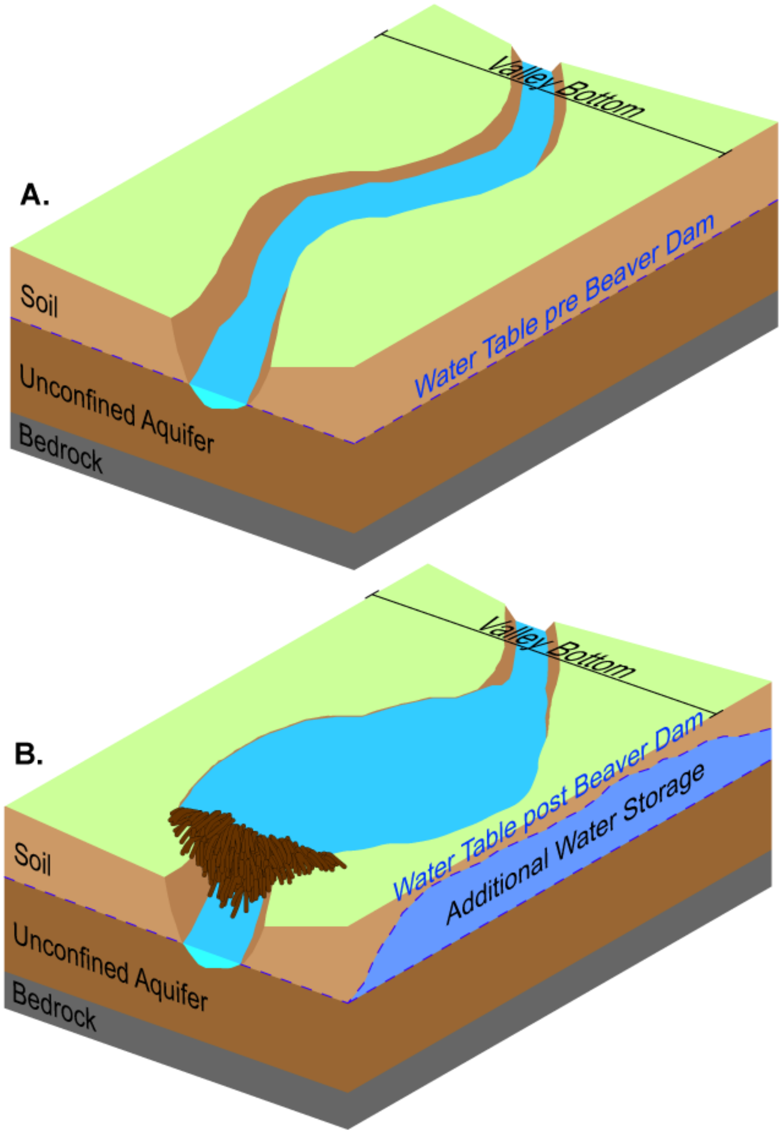


Figure 3.1. Theoretical illustration of the extent to which beaver may increase surface water and groundwater storage.

METHODS

Study Area

From its headwaters in the Uinta Mountains of northern Utah, the Bear River flows through Wyoming, back into Utah, into Idaho, and into Utah once more before terminating in the Great Salt Lake (Figure 3.2). The river drains a 19,450 km^2 basin, comprised of six 8 digit hydrologic unit subbasins (HU8) and 195 12 digit hydrologic unit subwatersheds (HU12), and ranges from 1300 m – 4000 m in elevation with a mean elevation of 2000 m (Figure 3.2). The Bear River is over 790 km in length, making it the longest river in North America that does not drain to an ocean. Combined with its 6591 km of perennial tributaries and its 1664 km of intermittent tributaries, it spans an incredibly diverse physiographic region and is a useful case study of relevance in the semi-arid West.

Streams in the Bear River basin of northern Utah, southeastern Idaho, and southwestern Wyoming (Figure 3.2) provide water for municipal, recreational, industrial, agricultural, and conservational uses, eventually terminating in the Great Salt Lake, a regionally important industrial, recreational, and ecological site. Proposals to construct water storage reservoirs in the Bear River basin to meet expected increases in water demand from future population growth (Bowen Collins & Associates and HDR Engineering, 2014) are a polarizing issue as there are concerns about maintaining natural hydrologic regimes and providing water for consumptive use (Wurtsbaugh *et al.*, 2016). Projected snowpack declines in the basin (Klos *et al.*, 2014) accentuate the necessity for identifying how hydrologic regimes may respond and identifying methods to manage the basin's water resources. Previous studies at various locations in the basin have examined the impacts of beaver dams on ecological systems (Lokteff *et al.*, 2013) and hydrological regimes (Majerova *et al.*, 2015), and beaver dam abundance throughout parts of the basin has been quantified (Macfarlane *et al.*, 2017). Additionally, special conservation regulations and management plans have been implemented to bolster and maintain existing beaver populations (Portugal *et al.*, 2015a; b; UDWR, 2010).

The Bear River is of regional importance providing water for wildlife, recreation, irrigation, municipalities, and hydroelectricity. Precipitation varies in both phase and magnitude dramatically throughout the basin. For example, the Central Bear HU8 receives 48% of annual precipitation as snow, with the Lower Bear-Malad HU8 receiving just 17% as snow. Annually, the basin receives an estimated 10.6 billion m^3 of precipitation with approximately 4.6 billion m^3 (~43%) in the form of snow (estimated with SNODAS data) and discharges 1.73 billion m^3 to the Great Salt Lake. However, with climate warming, precipitation regimes for much of the basin may shift to include more rain and less snow (Figure 3.3, Kloss et al., 2014). Combined maximum storage of the twenty-eight major reservoirs (i.e. dams 50 feet or more in height, with a normal storage capacity of 5,000 acre-feet or more, or with a maximum storage capacity of 25,000 acre-feet or more) in the drainage is 383.1 million m^3 (USACE, 2005), and the state of Utah is exploring options for constructing additional reservoirs to store 33.3 to 271.4 million m^3 of water to meet anticipated water demands from population growth (Bowen Collins & Associates and HDR Engineering, 2014).

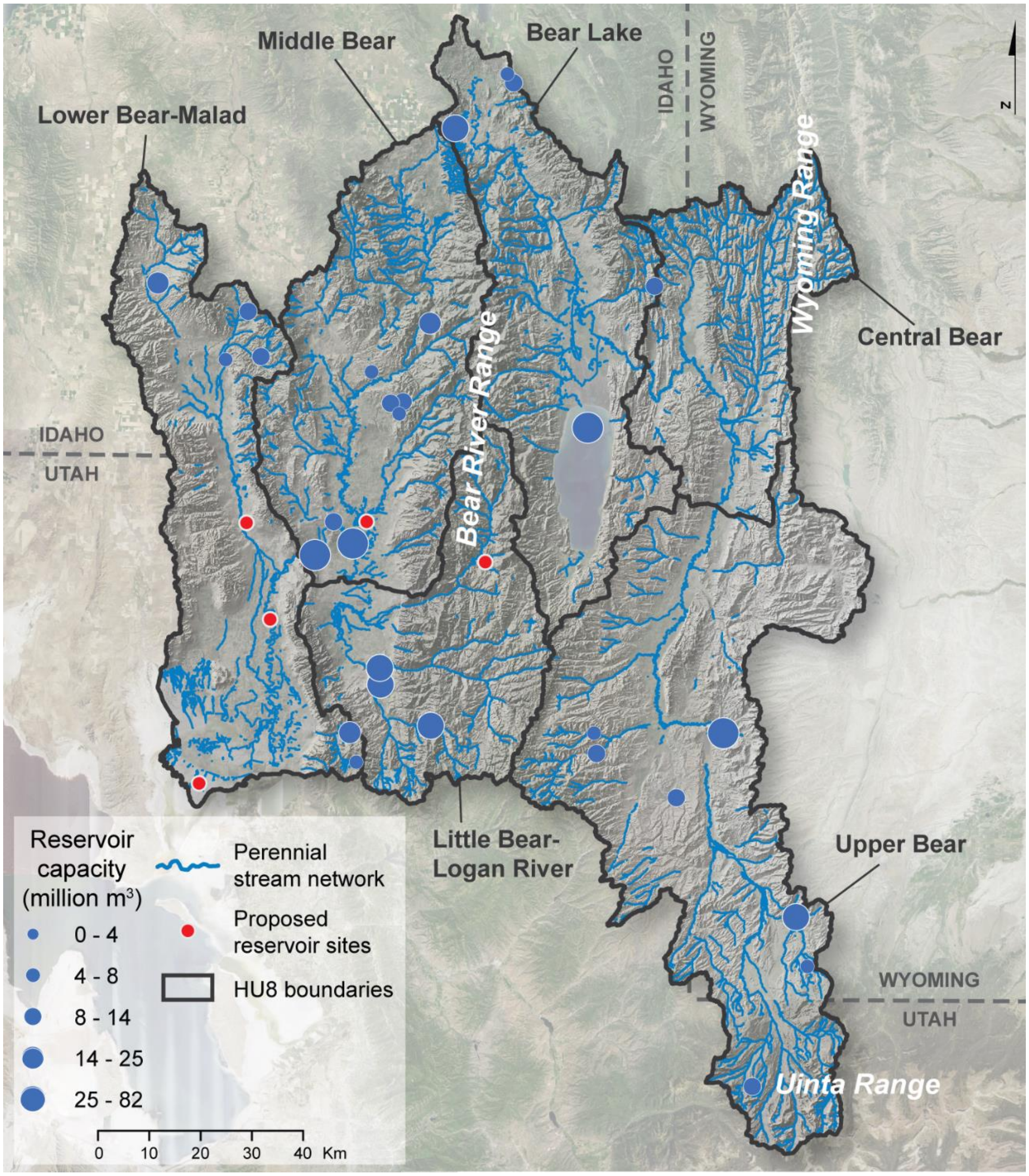


Figure 3.2. The National Hydrography Dataset perennial stream network, existing major reservoirs, locations of proposed reservoirs, and 8 digit hydrologic units (HU8) for the Bear River basin.

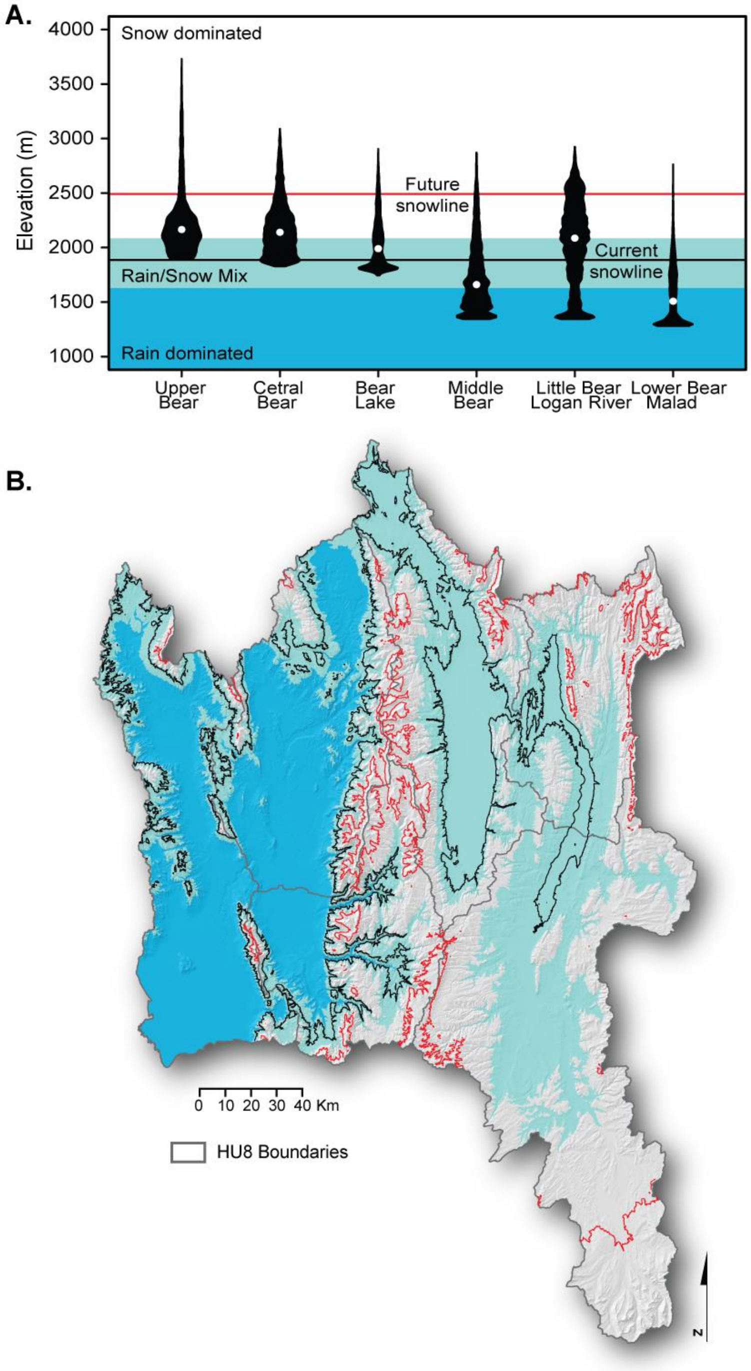


Figure 3.3. (A)Violin plots of contrasting elevation distributions (i.e. hypsometry) for 8 digit hydrologic units (HU8) in the Bear River basin with white circles showing the median elevation of each distribution. Estimates of precipitation types dominating each elevational segment and estimates of current and projected snowline elevation are also shown to illustrate how precipitation regimes may change throughout the basin. (B) Spatial extent of precipitation regimes with current snowline (black contour @ 1900 m) and projected future snowline (red contour @ 2500 m) with 4˚C warming. Adapted from Tennant et al. (2015).

Modeling Beaver Pond Water Storage

Beaver dam capacity. Estimates of maximum beaver dam capacity were calculated using the BRAT capacity model (Macfarlane *et al.*, 2017). This model calculates maximum dam density for a stream reach based on vegetation to provide woody dam building materials, geomorphic characteristics, and hydrology. Briefly, following Macfarlane et al. (2017) for preparing BRAT inputs, stream reaches were represented by segmenting perennial streams from the US Geological Survey (USGS) National Hydrography Dataset (NHD) into 300 m reaches (USGS, 2016). Annual base flows and flow of the average two-year flood were calculated from USGS regional equations for Region 1 of Utah (Wilkowske *et al.*, 2008). LANDFIRE existing vegetation cover (EVT) (LANDFIRE, 2016) classifications were used to represent current vegetation types. Dam densities from the BRAT capacity model were converted from dams per kilometer to dam counts by dividing by 1000 and multiplying by the reach length (m), resulting in a maximum number of dams a given stream reach could support. A percentage of the upper dam limit for each 12 digit hydrologic unit (HU12) in the Bear River basin was modeled under four different capacity scenarios, 5%, 25%, 50%, and quasi 100% (100% of dam complex capacity) of maximum dam capacity. These dam capacity estimates are likely conservative, as beaver are known to occupy portions of many streams mapped as intermittent in the basin.

Beaver dam placement simulations. The BRAT capacity model provides spatial estimates of maximum beaver dam density but does not simulate the location of individual beaver dams. We placed beaver dams using the BRAT estimated capacities as an upper limit. Dam location simulations were generated for the number of dams estimated by the four different dam capacity scenarios: %5, 25%, 50% and quasi 100% of maximum dam capacity to get a total count in each HU12 watershed. The total number of dams were distributed according to the BRAT densities on stream reaches with the assumption that the highest quality stream segments would be filled to maximum capacity before lower quality segments were colonized (Fretwell, 1972; Fretwell and Calver, 1969). The maximum number of dams a stream reach could support was calculated as the product of the length of the stream segment (m) and the estimated dam density (dams/m) as described above. For each HU12, stream segments were ranked according to dam capacity estimates, we considered the highest capacity estimates to represent the best habitat (Fretwell, 1972; Fretwell and Calver, 1969). Starting with the top ranking 300 m stream reach, a random number of dams were generated from a lognormal distribution with mean 1.55 and variance 0.72 representing the number of dams per dam complex (Chapter 2). These dams were spaced evenly spaced along the reach, dams continued to be added to reaches until the total number of dams specified for each scenario for a HU12 was obtained, or until a dam complex had been placed on all stream reaches in a HU12. In the event that the number of dams selected from the complex size distribution was greater than the maximum estimated capacity of the stream reach, the maximum dam capacity estimate was used. This method underestimates the total number of dams for a 100% dam capacity scenario as the number of dams selected from the complex size distribution will often be less than capacity estimates for reaches with high quality habitats. Therefore, under the quasi 100% dam capacity scenario all reaches that can support beaver dams are occupied by one complex (i.e. 100% dam complex capacity), but some of these reaches may not be at 100% of estimated dam capacity.

Water storage. Changes to water storage facilitated by beaver dams can be partitioned into two categories, water that is impounded and stored above ground in beaver ponds, and increases to groundwater table elevation resulting from increased infiltration. Increases in ponded storage were modeled using the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA) presented herein (Chapter 2). Our implementation of BD-SWEA was parameterized exactly as presented in Chapter 2, using a 10 m DEM from the National Elevation Dataset (NED) to represent topography. Modeled dams were classified as primary or secondary at probabilities of 0.15 and 0.85, respectively. Heights of modeled dams were determined by randomly sampling the height distribution for each dam type (primary or secondary) 1000 times (see Chapter 2 herein for height distribution parameters of primary and secondary dams) and taking the median value of the resulting distribution. The height of primary dams was modeled from a square root normal distribution with mean 1.14 m and variance 0.20 m and secondary dams from a square root normal distribution with mean 0.92 m, and variance 0.17 m. To account for potential differences in water storage volumes resulting from variability in dam heights, the 0.025 and 0.975 quantiles of the sampled dam height distribution were also modeled, giving results for low, median, and high estimates of dam height and water storage. Sampling the dam height distribution 1000 times for each dam provided stability between modeled dam heights, the number of times this distribution is sampled could be adjusted to increase dam height stochasticity.

To estimate groundwater table changes we implemented MODFLOW, the USGS three dimensional third-order finite groundwater model (Harbaugh, 2005) for valley-bottoms in our study area. We found the Newton formulation (NWT) of MODFLOW to be more reliable than the basic MODFLOW package when modeling HU12 watersheds (Niswonger *et al.*, 2011). Groundwater modeling was limited to the valley-bottom adjacent to perennial streams for which beaver dam capacity was estimated to limit model computation time and provide a realistic modeling domain representing locations where beaver dams may actually influence groundwater. The valley bottom consists of the stream channel and the adjacent floodplain (Fryirs *et al.*, 2016; Gilbert *et al.*, 2016), and as beaver dams are built in stream channels (often extending onto floodplains) we would not expect their effects to perpetuate onto hillslopes. Valley bottom extents were delineated using the Valley-Bottom Extraction Tool (V-BET) and V-BET outputs were validated and edited to resolve any inconsistencies following the methodology of Gilbert *et al.* (2016). We modeled the valley-bottom aquifer as a single layer with the aquifer bottom 10 m below the valley bottom surface on a grid of the same extent and resolution (10 m) as the NED DEM input to BD-SWEA. This simplified modeling approach was implemented as our study area consisted of a large basin and our objective was to quantify changes in groundwater elevations and not produce a detailed model of groundwater dynamics. The NED DEM also represented the model top, or surface elevation of the valley-bottom. We parametrized soil properties for MODFLOW with mean horizontal and vertical hydrologic conductivity values for each HU12. Estimates of hydraulic conductivity were obtained through area- and depth-weighted averages for the US Department of Agriculture’s (USDA) Soil Survey Geographic (SSURGO) database

(Soil Survey Staff) calculated by Wieczorek (2014). We used a single value for each vertical and horizontal conductivity by averaging values within the valley bottom of each HU12. For instances where no soil data were available for a HU12, the mean valley bottom value for the HU8 was used.

Four steady-state MODFLOW-NWT simulations were run for each HU12. The first simulation represented conditions with no beaver dams. This was accomplished by setting constant head boundaries along a rasterized stream network with the hydraulic head value equal to the stream elevation (DEM value) at all points along the rasterized network (Figure 3.4). The three other MODFLOW simulations were for the three dam height scenarios (low, median, and high). In these simulations the constant head boundaries were adjusted to include any areas predicted by BD-SWEA to be inundated by beaver ponds. The hydraulic head at locations inundated by beaver ponds were set as the surface elevation of the modeled beaver pond (Figure 3.4), we adjusted the model top (or valley-bottom surface) to reflect these changes. Change in water table elevation for each dam height scenario was calculated as the baseline water table elevation subtracted from the water table elevation after beaver dam construction, producing positive values where water tables increased in elevation and negative values where they decreased. Changes in water table elevation were converted to volumes as the product of water table elevation change, soil field capacity (area- and depth-averaged from the SUURGO database (Wieczorek, 2014)), and model grid resolution. To improve model results and reduce computational run time, we divided the study area by HU12 and ran each HU12 through MODFLOW individually, then merged the results together. We streamlined and automated this workflow using the flopy python module (http://modflowpy.github.io/flopydoc/introduction.html).

To build confidence that MODFLOW estimates were reliable, we leveraged empirical data on groundwater observations in beaver influenced stream reaches. We used data from a previous study in the Bear River basin, Curtis Creek, UT (Majerova *et al.*, 2015), and an ongoing study at Bridge Creek, OR (Evans *et al.* In Preparation) for which we were able to obtain empirical data (Figure 3.5). At each study site, groundwater wells were installed to monitor the effects of beaver dam construction. At the Curtis Creek site, groundwater monitoring wells were installed in 2008 and beaver colonized the site in 2009. A detailed topographic survey of the site in 2012 provided information about the size and location of beaver dams at the site. Using these topographic data, we modeled beaver pond depth and surface area with BD-SWEA, and changes to groundwater with MODFLOW, as described above. We then compared the modeled change in groundwater elevation with the observed change in groundwater elevation between 8/22/2008 and 9/25/2012, when water table levels were measured with a depth sounder.

At the Bridge Creek study site, groundwater wells were installed in 2007 after beaver had already colonized the stream reach, and location specific data for beaver dams were not available until 2011 (Evans *et al.* In Preparation). Beaver dam locations were marked in May and December of each year and the condition (intact, breached, or blown-out) of each beaver dam was recorded, however, dam heights for each dam were not available. We followed a similar procedure for validation on Bridge Creek, comparing modeled changes in groundwater elevations to measured changes in groundwater elevations between December 2011 and December 2015. We calculated the change in groundwater elevation at each well from 2011 to each year from 2012 – 2015 using the average groundwater elevation for the month of December as beaver dam locations were collected throughout the month. With BD-SWEA we modeled both intact and breached dams on Bridge Creek using the methods described above to determine median dam height as actual dam heights were not available. Though the effects of breached dams on groundwater tables are likely not as great as intact dams they still have some effect.

Projected Snowpack Decreases

To quantitatively contextualize how storage from beaver ponds may be able to offset declining snowpack we developed a relationship between elevation and average annual peak snow water equivalent (SWE), then adjusted this relationship to simulate warming scenarios from 1-4 ˚C following the methods of Tennant et al. (2015b). Peak SWE is used by water managers to estimate streamflow and guide reservoir operations (Barnett *et al.*, 2005; Christensen *et al.*, 2004). SWE loss can then be estimated as the difference between the current relationship and an expected future relationship. We developed the relationship between elevation and SWE by averaging peak SWE values from the National Weather Service's spatially gridded (1 km) Snow Data Assimilation System (SNODAS) (Barrett, 2003; Carroll *et al.*, 2003), a snow mass and energy model based on SNTHERM.89 (Jordan, 1991), for the 2004-2015 water years. Elevation values for each value of mean SWE were obtained by sampling a DEM, identical in resolution and extent to the SNODAS grid, at each location where averaged peak SWE values were available. The relationship between elevation and mean SWE was described by fitting Richard’s growth function to relate elevation to mean peak SWE. We chose to use

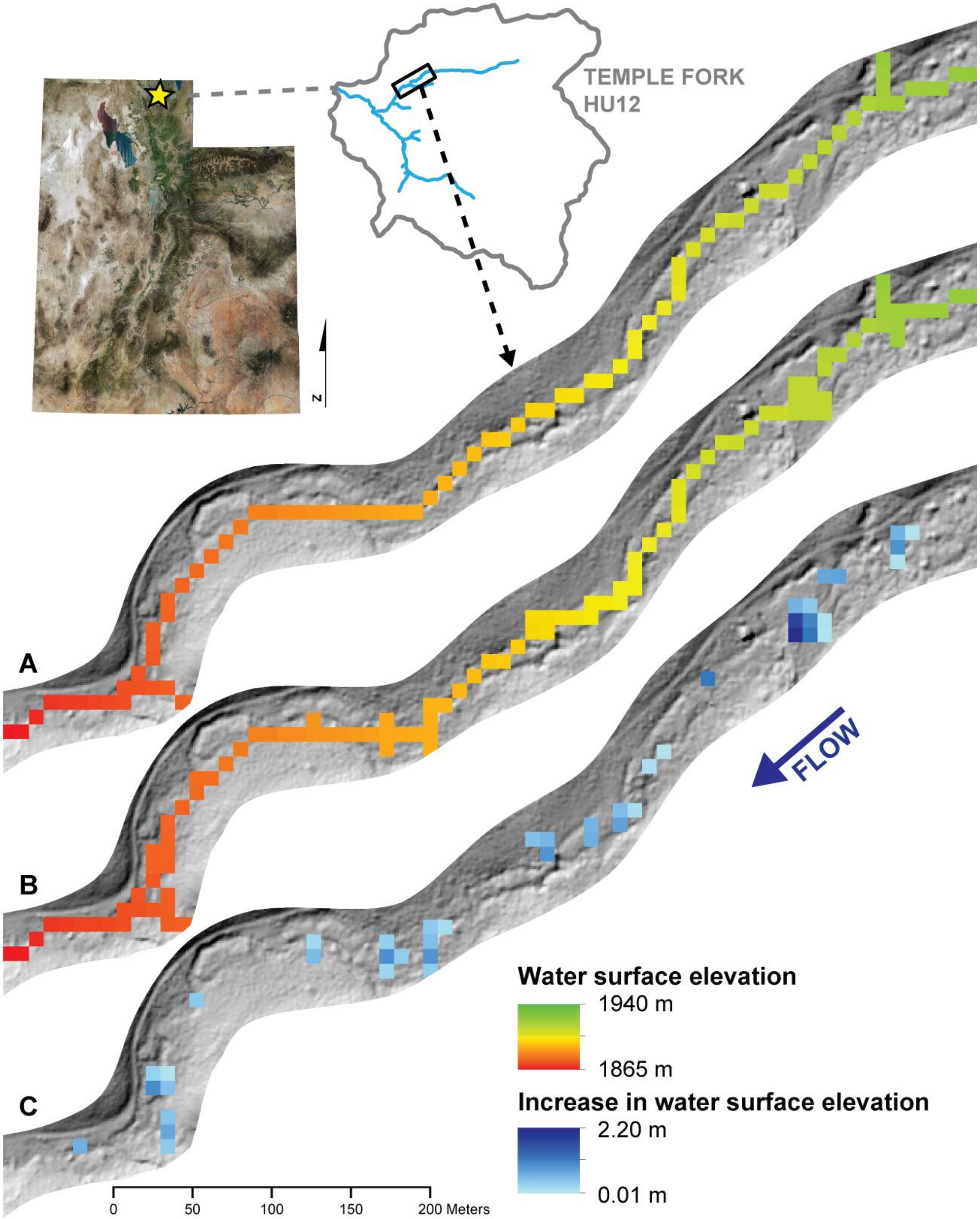


Figure 3.4. (A) Initial boundary conditions for head elevation, (B) head elevations to represent beaver ponds, (C) and the difference between initial head values and beaver pond head values. This difference is equal to the depth of modeled beaver ponds.

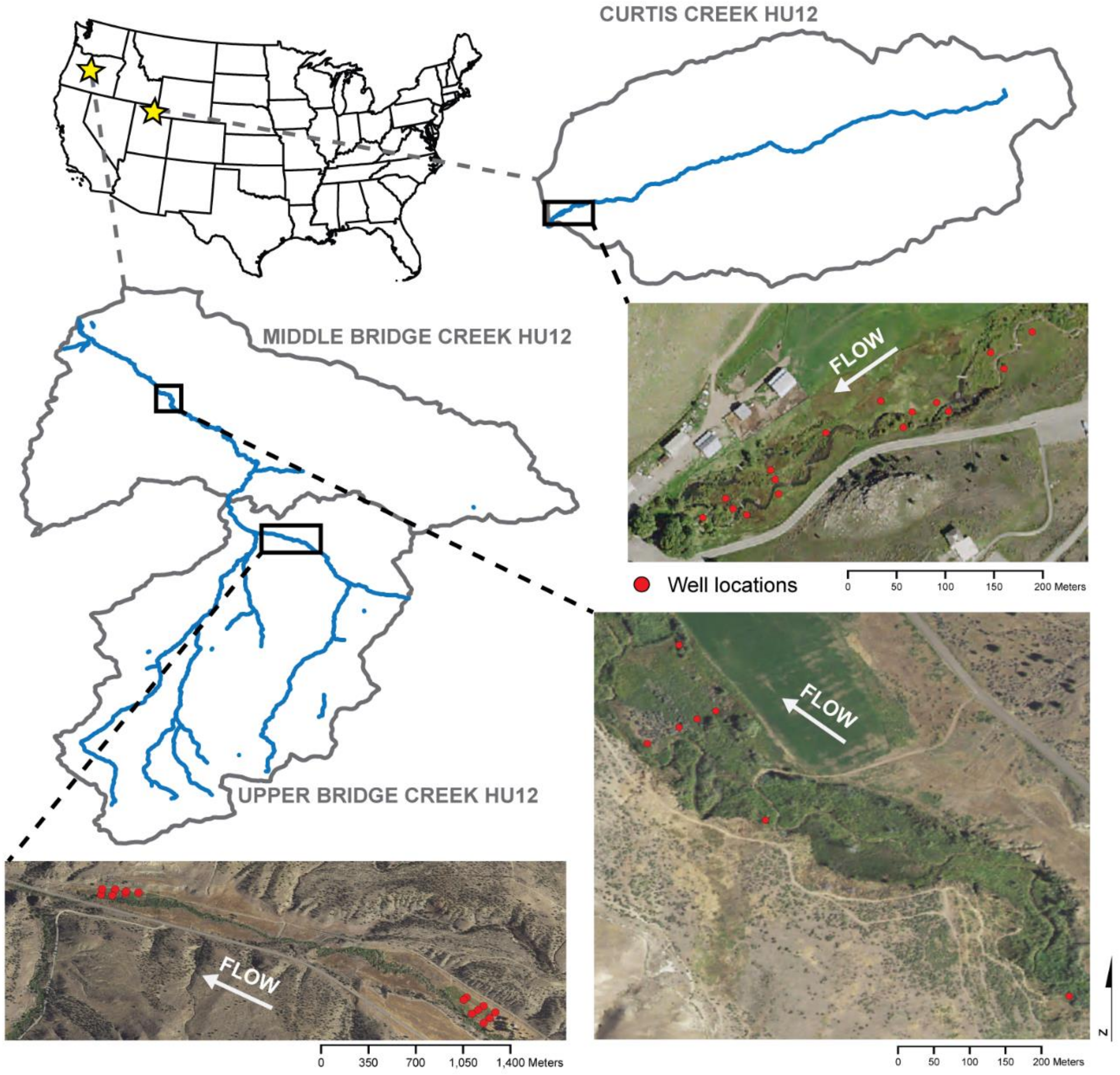


Figure 3.5. Groundwater well locations at the Bridge Creek and Curtis Creek Study sites.

Richard’s growth function as three of the four fitted parameters can meaningfully describe measured variables (Tennant *et al.*, 2015b) relating to SWE. λ describes snowline elevation, A maximum SWE (mm), and M the maximum slope of the relationship with v controlling the shape of the curve. Warming was simulated by applying the moist adiabatic lapse rate of -0.65 ˚C per 100m to move the snowline elevation (λ) upward under each warming scenario. No other parameters of the Richard's equation were manipulated to simulate warming scenarios. Estimated decrease in mean maximum SWE for each raster cell was calculated as the estimated mean maximum SWE under a future warming scenario subtracted from the initial estimated mean maximum SWE (i.e. current condition).

Three primary mountain ranges exist in the Bear River drainage, the Bear River Range in northern Utah and Southern Idaho (an extension of the Wasatch Range), the Uinta Range in northeastern Utah, and the Wyoming Range in western Wyoming with the majority of the basin draining from the Bear River Range (Figure 3.2). We examined the basin SWE – elevation in the context of these mountain ranges to qualitatively determine if differences in the relationship occurred between the ranges. We observed differences in the SWE – elevation relationship between Uinta Range and the combination of the Bear River and Wyoming ranges (Figure 3.3), and correspondingly developed two fits for the Richard's equation.

RESULTS

Beaver Dam Capacities

Of the 195 HU12s in the Bear River basin there were 11 which did not contain perennial streams, or contained perennial streams which could not support beaver. Thus, beaver dam capacity was modeled for the remaining 184 HU12s. The Beaver Restoration Assessment Tool estimated a maximum dam capacity of 41,848 dams for the 6591 km of streams in the Bear River basin (Figure 3.6), resulting in an overall maximum dam density of 6.3 dams/km (Table 3.1). For scenarios with beaver dams modeled at 5%, 25%, 50%, and quasi 100% of maximum estimated capacity a total of 1779, 9396, 19,191, and 34,897 individual dams were modeled, representing 2.8%, 22.4%, 46.0%, and 83.4% of maximum estimated dam capacity, respectively (Figure 3.7).

In all, we modeled potential water storage increases under four different beaver dam capacity scenarios (5%, 25%, 50%, and quasi 100% of maximum estimated dam capacity) and potential volumetric water losses from decreasing mean peak SWE under four warming scenarios (+1 ˚C, +2 ˚C, +3 ˚C, and +4 ˚C) for the entire Bear River basin. To bound the groundwater simulations, perennial valley bottoms were modeled for each HU8 watershed (Table 3.1) and ranged from 3.7% to 12.4% of the total drainage area, and made up 7.9% of the entire Bear River Basin.

Table 3.1. Length of perennial streams for each HU8, maximum estimated dam capacity, and percent of the landscape occupied by valley-bottoms (VB) of perennial streams.

HU8	**Stream Length (km)**	**Dam Capacity**	**Dam Density (dams/km)**	**HU8 Area (km^2)**	**VB Area (km^2)**	**VB Percent**
Upper Bear	1605	13,331	8.3	5203	471	9.1%
Central Bear	1027	7966	7.8	2123	224	10.6%
Bear Lake	975	6198	6.4	3281	407	12.4%
Middle Bear	1208	5889	4.9	3324	164	4.9%
Little Bear - Logan River	651	4939	7.6	2290	84	3.7%
Lower Bear - Malad	1124	3526	3.1	3242	184	5.7%
Entire Basin	**6591**	**41,848**	**6.3**	**19,463**	**1535**	**7.9%**

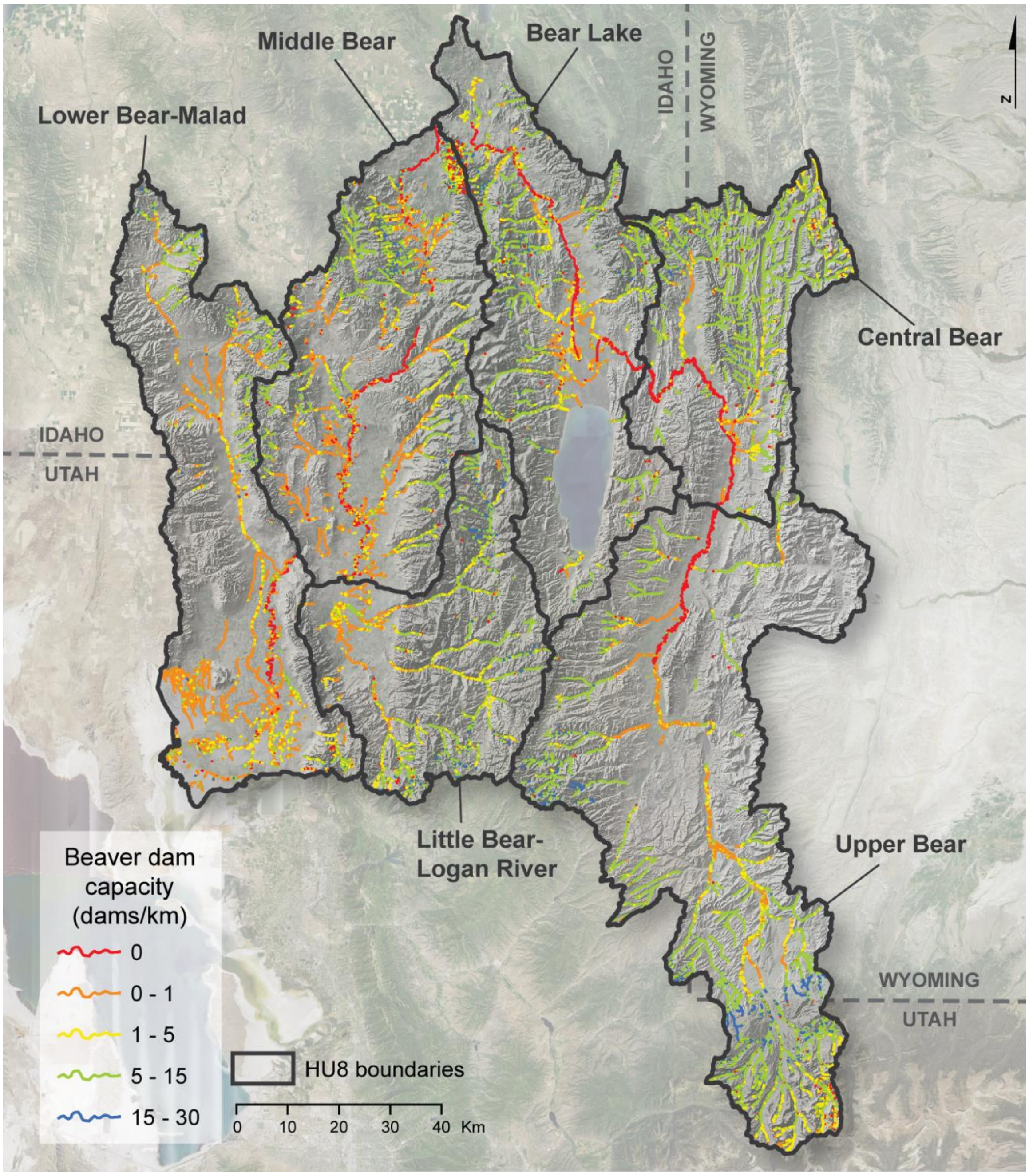


Figure 3.6. Maximum estimated beaver dam capacity for the Bear River basin.

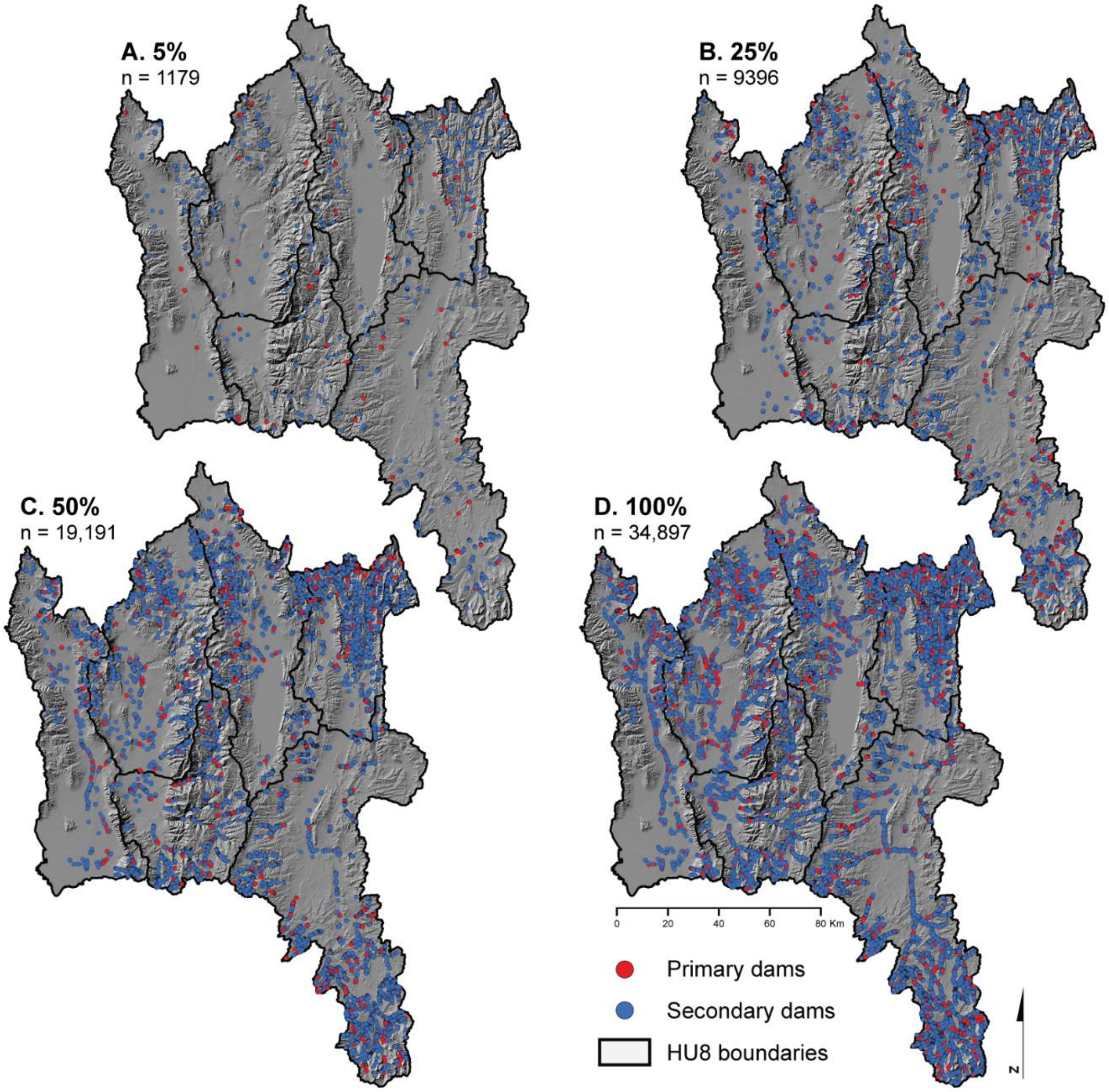


Figure 3.7. Spatial distribution of the primary and secondary beaver dams for which volume was modeled with BD-SWEA and MODFLOW at (A) 5%, (B) 25%, (C) 50%, and (D) quasi 100% of maximum dam capacity estimated by BRAT.

Beaver Dam Water Storage

MODFLOW validation. Regressing the modeled changes to groundwater elevation against observed changes to groundwater elevation over the period of August 2008 to September 2012 at Curtis Creek, UT produced a linear relationship described by an intercept of 0.19 (t = 2.541, p = 0.024) and slope of 0.67 (t = 2.16, p = 0.049). A simultaneous linear hypothesis test indicated this relationship did not statistically differ from an intercept of zero and slope of one at the 95% confidence level (F = 3.27, p = 0.068; Figure 3.8). However, a paired t-test shows the difference between modeled and observed points to be significantly different than zero (t = 2.34, df = 15, p = 0.034). At Bridge Creek, OR the linear relationship between modeled and observed changes to groundwater is described by and intercept of 0.17 (t = 2.83, p = 0.006) and slope of 0.47 (t = 2.06, p = 0.044). With a simultaneous linear hypothesis test, this relationship was determined as differing significantly from an intercept of zero and slope of 1 (F = 4.08, df = 2, p = 0.022; Figure 3.8). A paired t-test indicated the difference between modeled and observed changes to groundwater at Bridge Creek did not differ significantly from zero (t = 1.62, df = 64, p = 0.111). These combined tests gave us confidence that the estimated increases in groundwater storage associated with beaver dam building activity were adequate for our purposes.

Beaver dam water storage. Using median dam height estimates, the total (surface water and groundwater) estimated water storage provided by beaver dams was 0.3 million m^3, 1.1 million m^3, 3.1 million m^3, and 6.6 million m^3 for each dam capacity scenario (Table 3.2, 3.3). The extreme values (0.025 quantile at 5% capacity and 0.975 quantile dam height at quasi 100% capacity) of water storage increases were 0.1 million m^3 (65 acre-feet) and 13.7 million m^3 (11,100 acre-feet). For 10 HU12s MODFLOW-NWT did not converge on a solution, thus we estimated no change in groundwater storage increases for these watersheds. With valley-bottoms covering 1535 km^2 of the Bear River basin (7.9%, Table 3.1), the changes to groundwater storage in the valley

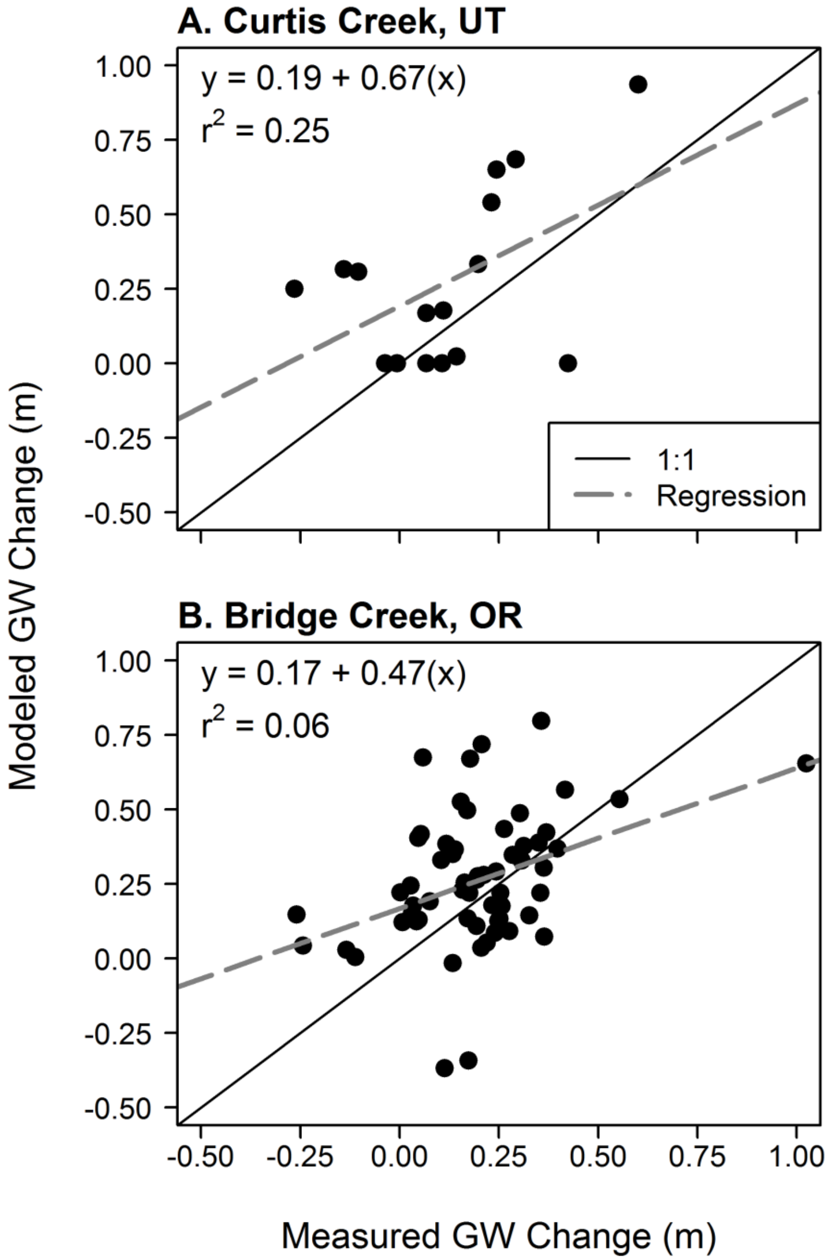


Figure 3.8. Linear regression validation of groundwater changes estimated with MODFLOW against groundwater elevation changes measured at wells via depth-sounder at (A) Curtis Creek, UT and pressure transducer at (B) Bridge Creek, OR.

bottoms accounted for 73.1%, 66.4%, 67.8%, and 71.7% of total estimated beaver induced water storage estimates for the entire basin under 5%, 25%, 50%, and quasi 100% dam capacity scenarios, respectively (Table 3.2, Figure 3.9).

Potential beaver dam water storage volume was tied to maximum dam density, with the Upper Bear HU8 (which has the highest dam density) estimated to provide the most potential beaver dam water storage and the Lower Bear-Malad HU8 (which has the lowest dam density) the least (Table 3.3). The number of modeled beaver dams was greatest in portions of the Uinta and Wyoming mountain ranges, and potential water storage increases spatially correspond to these regions (Figure 3.10). For median dam heights, mean surface water storage ranged from 45.8 to 54.3 m^3 per pond and mean increases to groundwater storage ranged from 134.1 to 191.3 m^3 per pond (Table 3.4).

Table 3.2. Estimated water storage for each dam capacity scenario with low, median, and high estimates of dam height. Values are million m^3.

		Modeled Storage Volume for Percent of Maximum Estimated Dam Capacity (million m^3)			
Storage Type	**Modeled Dam Height Quantile**	**5%**	**25%**	**50%**	**quasi 100%**
Surface	0.025	0.02	0.12	0.28	0.54
	0.5	0.08	0.44	1.00	1.88
	0.975	0.17	0.99	2.23	4.26
Ground	0.025	0.05	0.35	0.77	1.86
	0.5	0.19	0.87	2.08	4.77
	0.975	0.21	1.69	4.02	9.42
Total	**0.025**	**0.08**	**0.47**	**1.05**	**2.40**
	0.5	**0.26**	**1.31**	**3.07**	**6.65**
	0.975	**0.38**	**2.68**	**6.26**	**13.68**

Table 3.3. The number of modeled primary and secondary beaver dams, total length of perennial stream (Stream Length), modeled dam density, total change in water storage (TS), change in surface water storage (SWS), and change in groundwater storage (GWS) at median dam height for each HU8 under each BRAT dam capacity scenario. Values for TS, SWS, and GWS are million cubic meters.

HU8	**BRAT capacity**	**Primary Dams**	**Secondary Dams**	**Stream Length (km)**	**Dam Density (dams/ km)**	**TS (acre-feet)**	**TS (mil. m^3)**	**SWS (mil. m^3)**	**GWS (mil. m^3)**
Upper Bear	5	87	455	1605	0.3	20.0	0.08	0.02	0.06
	25	461	2498	1605	1.8	144.6	0.53	0.18	0.36
	50	973	5193	1605	3.8	320.7	1.26	0.40	0.86
	100	1703	9572	1605	7.0	594.1	2.57	0.73	1.84
Central Bear	5	60	305	1027	0.4	13.7	0.04	0.02	0.03
	25	332	1659	1027	1.9	85.1	0.28	0.10	0.17
	50	581	3350	1027	3.8	164.5	0.55	0.20	0.35
	100	1074	6115	1027	7.0	305.8	1.23	0.38	0.86
Bear Lake	5	40	235	975	0.3	10.3	0.06	0.01	0.05
	25	218	1158	975	1.4	54.4	0.16	0.07	0.10
	50	418	2327	975	2.8	118.3	0.52	0.15	0.37
	100	751	4088	975	5.0	224.6	1.24	0.28	0.97
Middle Bear	5	44	228	1208	0.2	7.1	0.02	0.01	0.01
	25	202	1170	1208	1.1	20.6	0.09	0.03	0.06
	50	418	2443	1208	2.4	88.9	0.29	0.11	0.18
	100	840	4394	1208	4.3	171.5	0.69	0.21	0.47
Little Bear - Logan River	5	32	165	651	0.3	6.6	0.05	0.01	0.04
	25	145	854	651	1.5	31.6	0.16	0.04	0.12
	50	331	1771	651	3.2	74.4	0.28	0.09	0.19
	100	547	3350	651	6.0	138.9	0.56	0.17	0.39
Lower Bear - Malad	5	22	106	1124	0.1	3.2	0.00	0.00	0.00
	25	126	573	1124	0.6	20.6	0.09	0.03	0.06
	50	204	1182	1124	1.2	42.4	0.17	0.05	0.12
	100	369	2094	1124	2.2	89.8	0.36	0.11	0.25
Entire Basin	**5**	**285**	**1494**	**6591**	**0.3**	**213.6**	**0.26**	**0.08**	**0.19**
	25	**1484**	**7912**	**6591**	**1.4**	**1059.2**	**1.31**	**0.44**	**0.87**
	50	**2925**	**16,266**	**6591**	**2.9**	**2492.5**	**3.07**	**1.00**	**2.08**
	100	**5284**	**29,613**	**6591**	**5.3**	**5393.7**	**6.65**	**1.88**	**4.77**

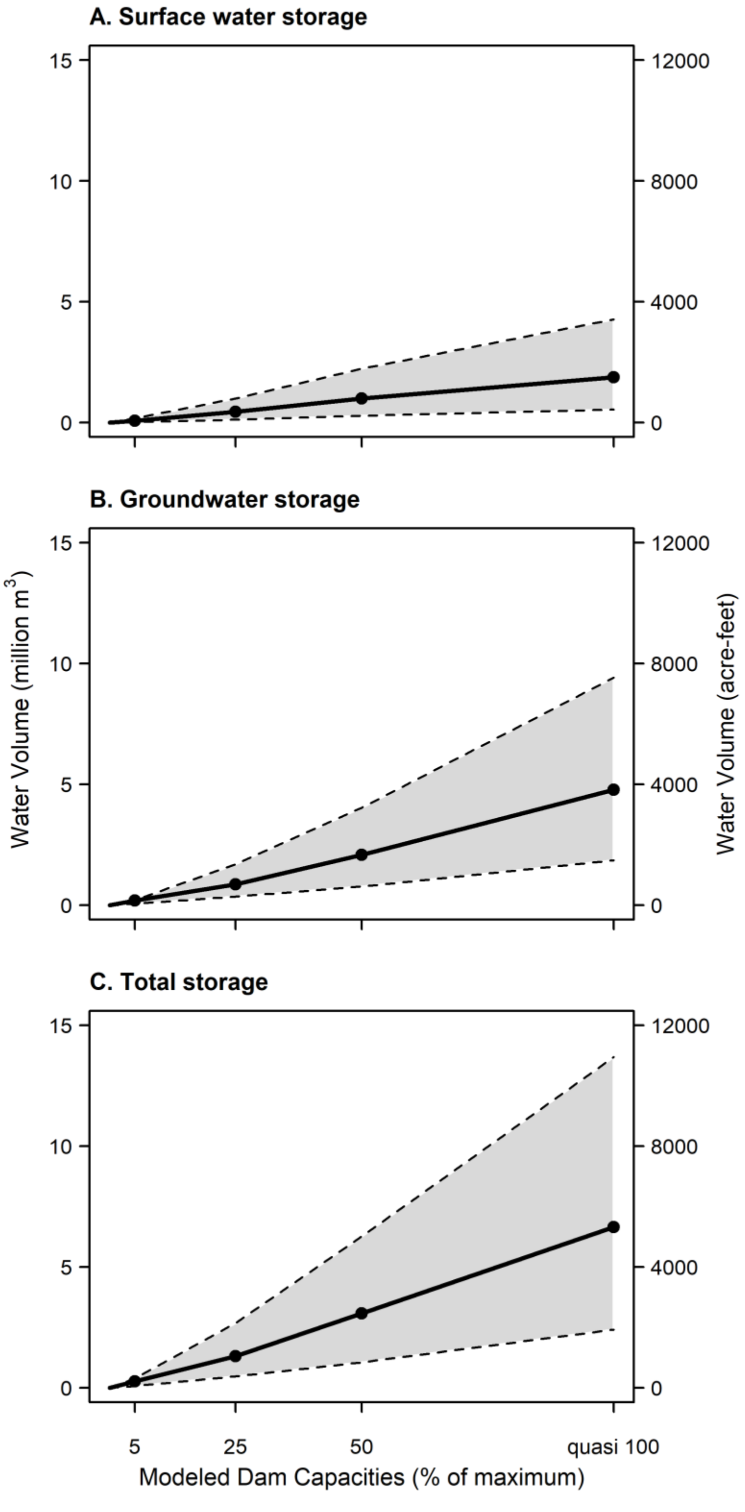


Figure 3.9. Estimates of water storage provided by beaver dams modeled at 5%, 25%, 50%, and quasi 100% of maximum dam capacity for 0.025, 0.5, and 0.975 dam height quantiles. The shaded area is the potential range of storage volumes between 0.025 and 0.975 dam height quantiles.

Table 3.4. Mean and standard deviation (SD) values of potential increases to surface water (SW) and groundwater (GW) for individual beaver dams.

BRAT capacity	**Modeled dam height quantile**	**Mean SW volume (m^3)**	**SD SW volume (m^3)**	**Mean GW volume (m^3)**	**SD GW volume (m^3)**
5	0.025	12.26	19.48	124.98	681.75
	0.500	45.78	57.03	134.07	259.60
	0.975	105.61	132.12	264.43	564.63
25	0.025	13.69	27.08	84.85	227.27
	0.500	49.88	60.81	165.30	303.61
	0.975	112.28	132.82	307.79	476.17
50	0.025	14.79	32.85	64.27	97.83
	0.500	52.34	63.24	155.79	193.43
	0.975	117.12	136.88	302.95	390.99
100	0.025	15.57	31.87	75.30	100.57
	0.500	54.31	64.34	191.26	248.96
	0.975	123.01	141.19	381.60	502.90

Projected Snowpack Decreases

Fitted estimates for the λ, A, M and v parameters of the Richard's equation representing the relationship between elevation and mean maximum SWE were 1955, 0.56, 616, and 3.4 for the Upper Bear HU8 and 1892, 653, 0.92, and 9.9 for all other HU8s, respectively. Under warming scenarios of 1 ˚C, 2 ˚C, 3 ˚C, and 4 ˚C lambda, which represents the elevation of the snowline, was shifted upward to 2121 m, 2288 m, 2455 m, and 2621 m for the Upper Bear HU8 and 2059 m, 2226 m, 2392 m, and 2393 m for the rest of the basin under each respective scenario (Figure 3.11). For the entire basin, water stored in snowpack decreased by 1.0 billion m^3, 1.9 billion m^3, 2.5 billion m^3, and 2.9 billion m^3 under 1 ˚C, 2 ˚C, 3 ˚C, and 4 ˚C warming scenarios at mean peak SWE

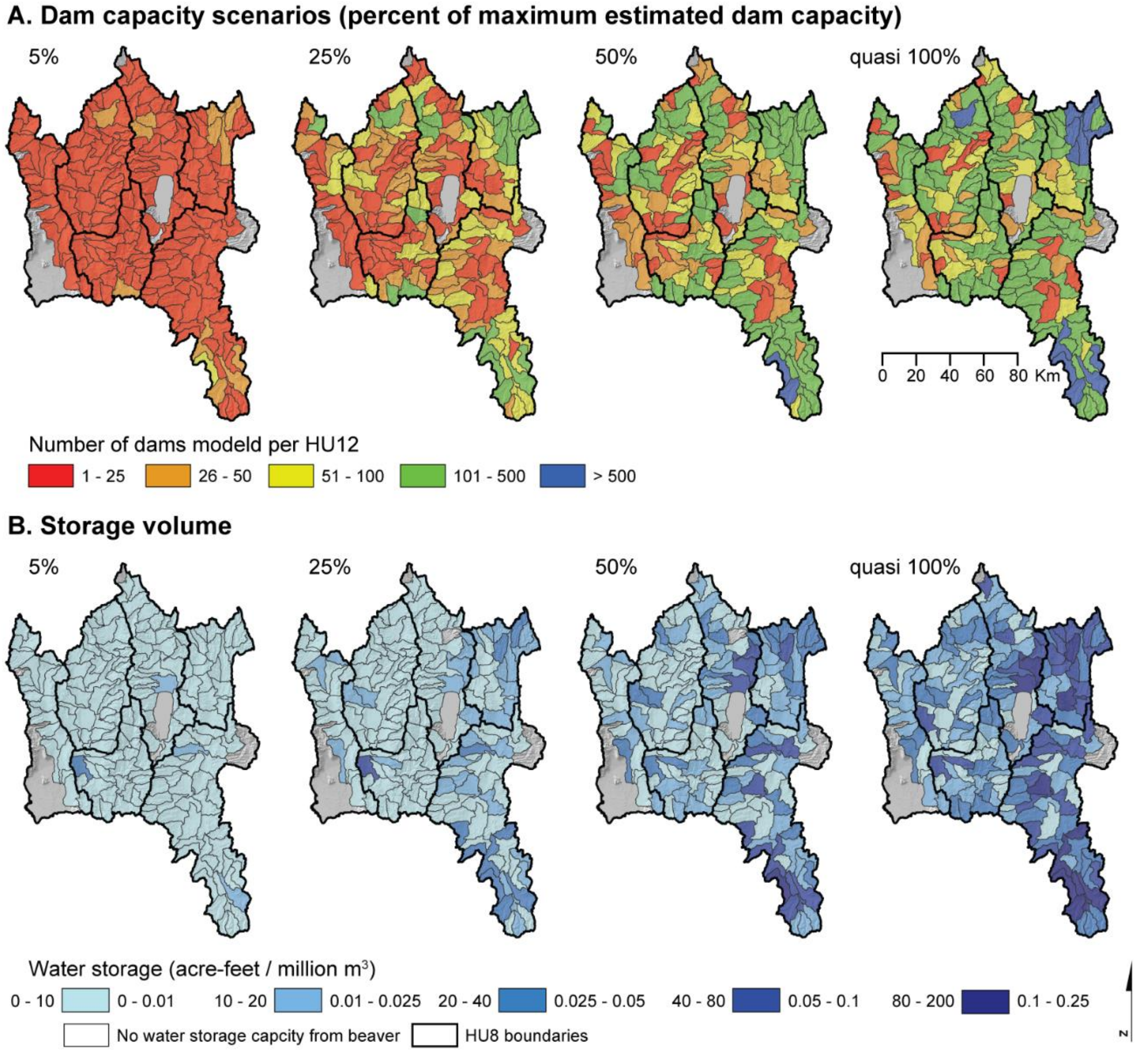


Figure 3.10. The number of beaver dams modeled and the potential change in water storage resulting from beaver dam construction for each HU12 in the Bear River basin under dam capacity scenarios of 5%, 25%, 50%, and quasi 100%.

(Table 3.5), this accounts for a loss of approximately 22%, 41%, 54%, and 63% in the basin's annual maximum peak snow water equivalent. The maximum estimated water storage increase from beaver dam construction (quasi 100% capacity scenario) accounts for 1.3%, 0.7%, 0.5%, and 0.4% of volumetric SWE losses under the respective warming scenarios of 1 ˚C, 2 ˚C, 3 ˚C, and 4 ˚C (Figure 3.12). Within the basin's valley bottoms we estimated losses from decreasing peak SWE to be 53.7 million m^3, 93.5 million m^3, 122.7 million m^3, and 143.9 million m^3, for respective warming scenarios. Storage created by beaver dams could account for 12.4%, 7.1%, 6.0%, and 4.6% of valley-bottom SWE loss under at quasi 100% of dam capacity under the considered warming scenarios (Figure 3.13).

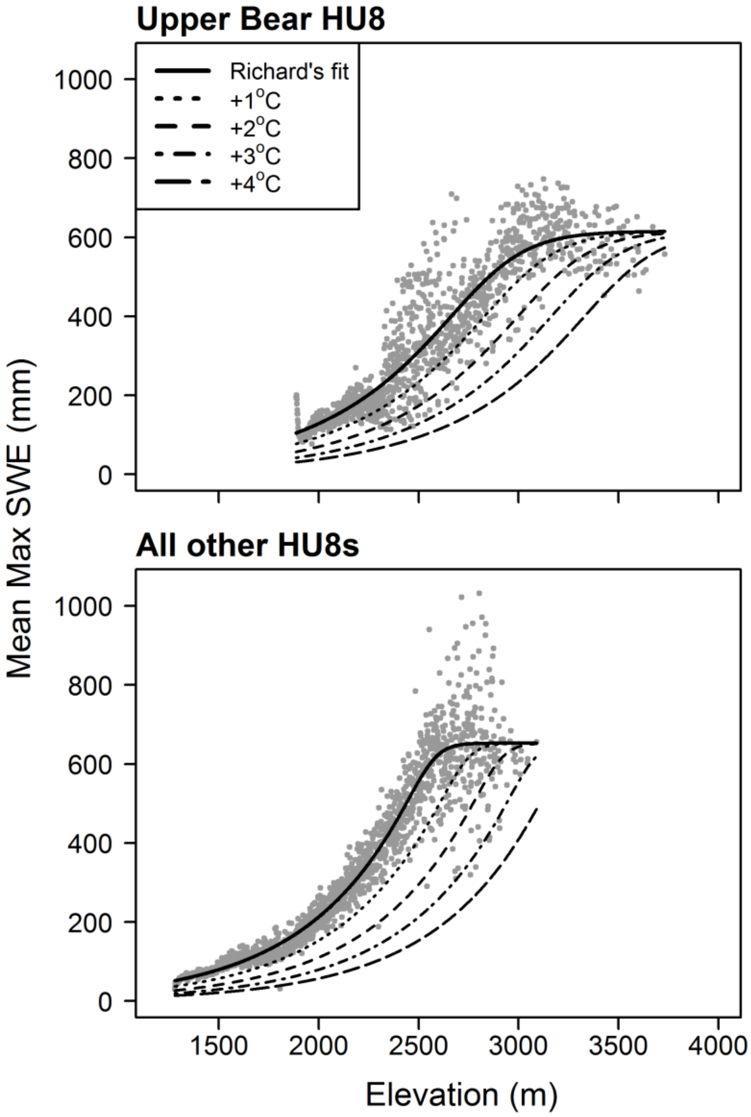


Figure 3.11. Richard's equation fit to the Upper Bear HU8, and all other HU8s in the Bear River basin. Gray points are mean maximum SWE for the 2004-2015 water years, the solid black line is the fit of Richard's Equation for the points, and dashed lines are adjusted fits for warming scenarios of 1 ˚C, 2 ˚C, 3 ˚C, and 4 ˚C. Points represent mean maximum SWE for water years 2004-2015 at 1 m elevation intervals.

Table 3.5. Estimated volumetric loss in SWE for each HU8 under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C. Values are million cubic meters and million acre-feet.

	Volumetric Peak SWE Loss (million m^3 / million acre-feet)							
HU8	**1˚C**		**2˚C**		**3˚C**		**4˚C**	
Upper Bear	248.97	0.20	451.01	0.37	611.89	0.50	737.06	0.60
Central Bear	167.22	0.14	303.37	0.25	408.63	0.33	485.92	0.39
Bear Lake	224.23	0.18	397.45	0.32	524.18	0.42	615.11	0.50
Middle Bear	140.07	0.11	246.20	0.20	323.85	0.26	379.57	0.31
Little Bear - Logan River	165.75	0.13	300.59	0.24	400.54	0.32	472.38	0.38
Lower Bear - Malad	97.59	0.08	168.71	0.14	219.98	0.18	256.71	0.21
Total	**1043.83**	**0.85**	**1867.34**	**1.51**	**2489.08**	**2.02**	**2946.76**	**2.39**

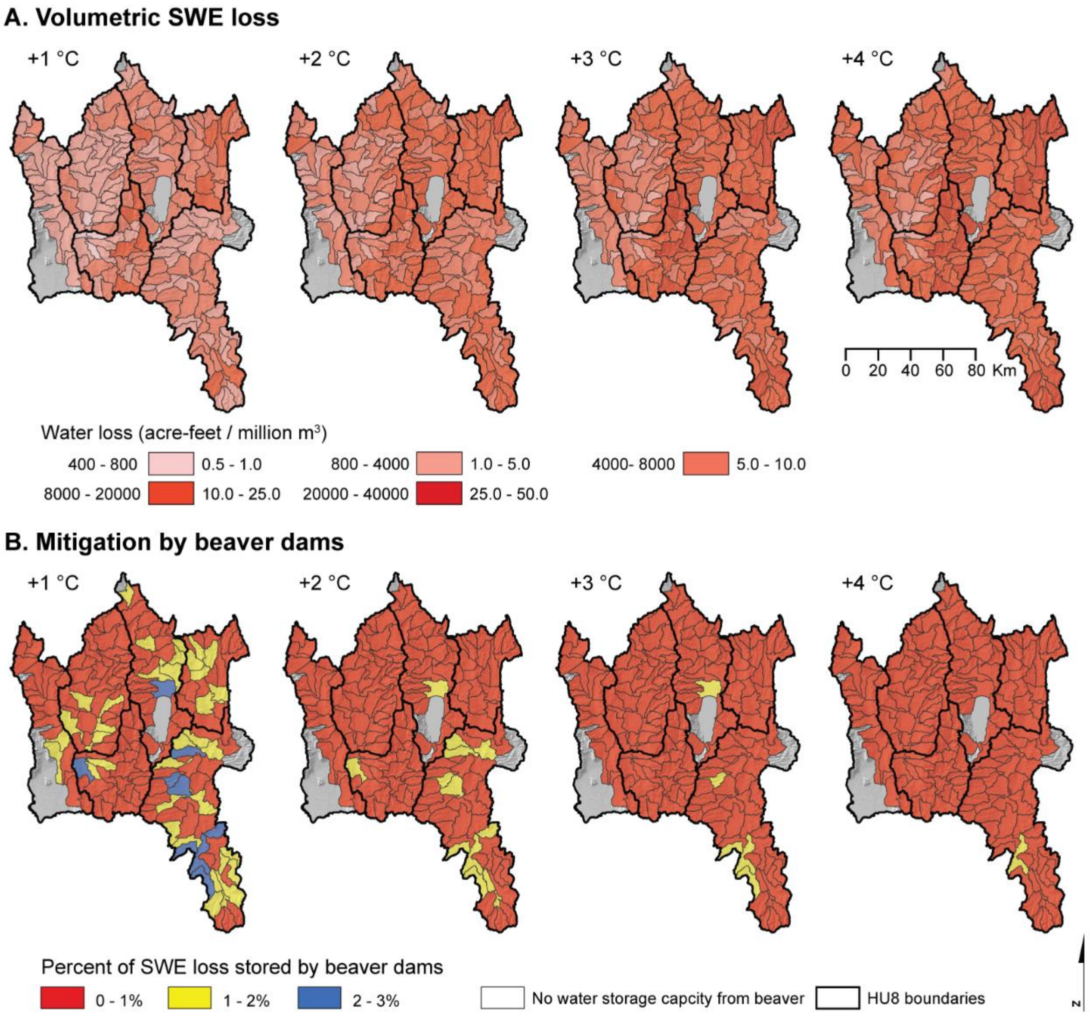


Figure 3.12. Volumetric SWE loss and percent of SWE loss that could mitigated by beaver dams of median dam height at quasi 100% of maximum dam capacity under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C for each HU12 in the Bear River basin.

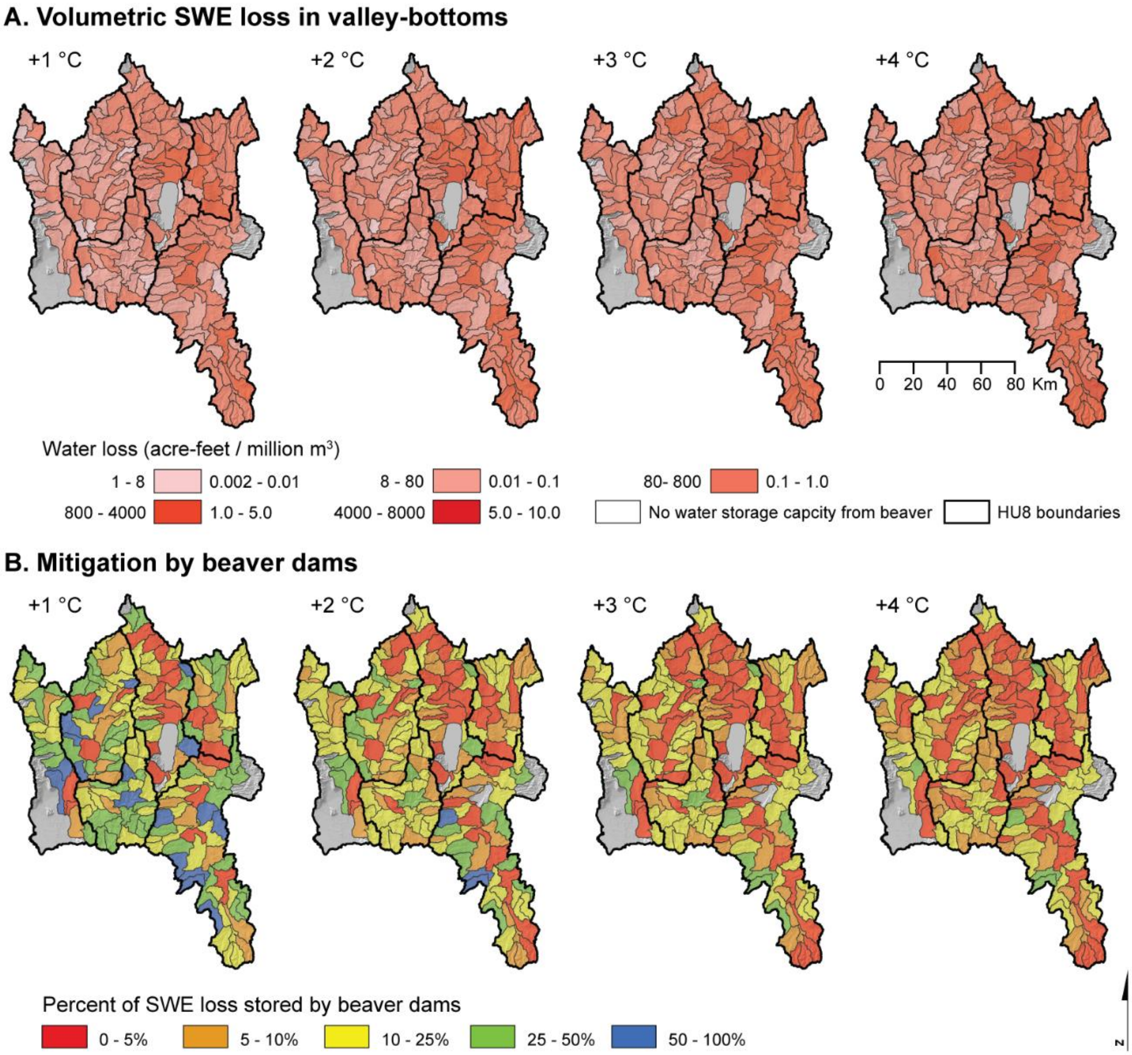


Figure 3.13. Volumetric SWE loss from valley-bottoms and percent of valley-bottom SWE loss that could be mitigated by beaver dams of median dam height at quasi 100% of maximum dam capacity under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C for each HU12 in the Bear River basin.

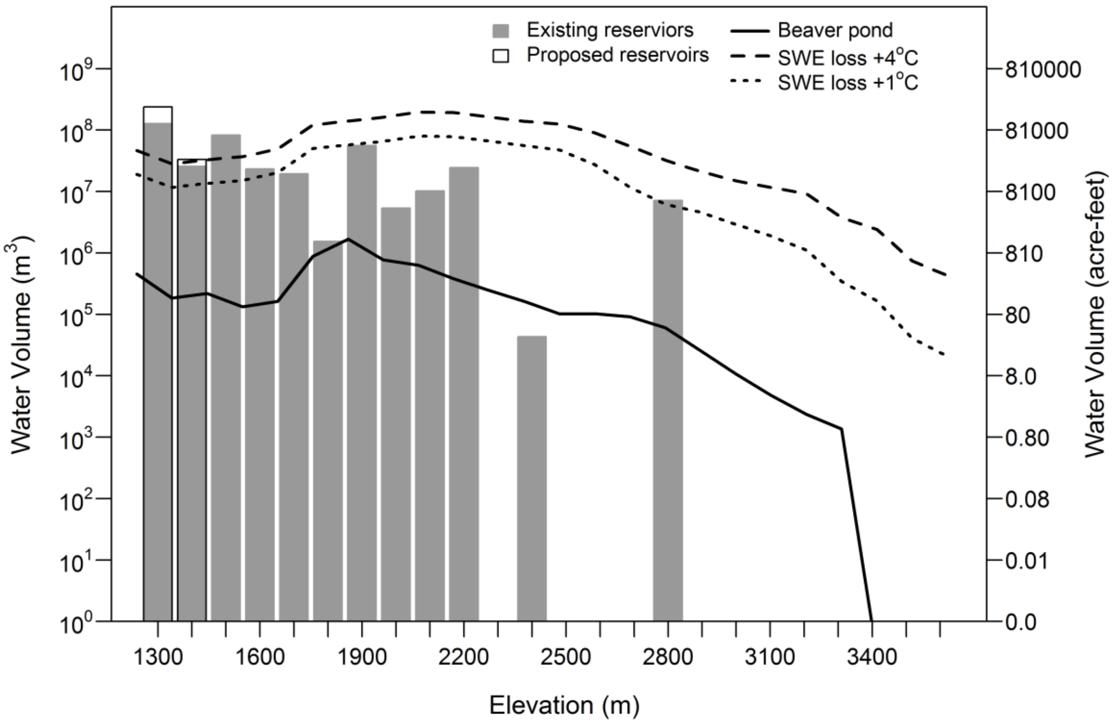


Figure 3.14. Existing reservoir storage, proposed increases to reservoir storage, maximum estimated storage from beaver dams of median height at quasi 100% of maximum estimated capacity, and estimated volumetric loss in mean maximum SWE under 1 ˚C and 4 ˚C warming scenarios by elevation.

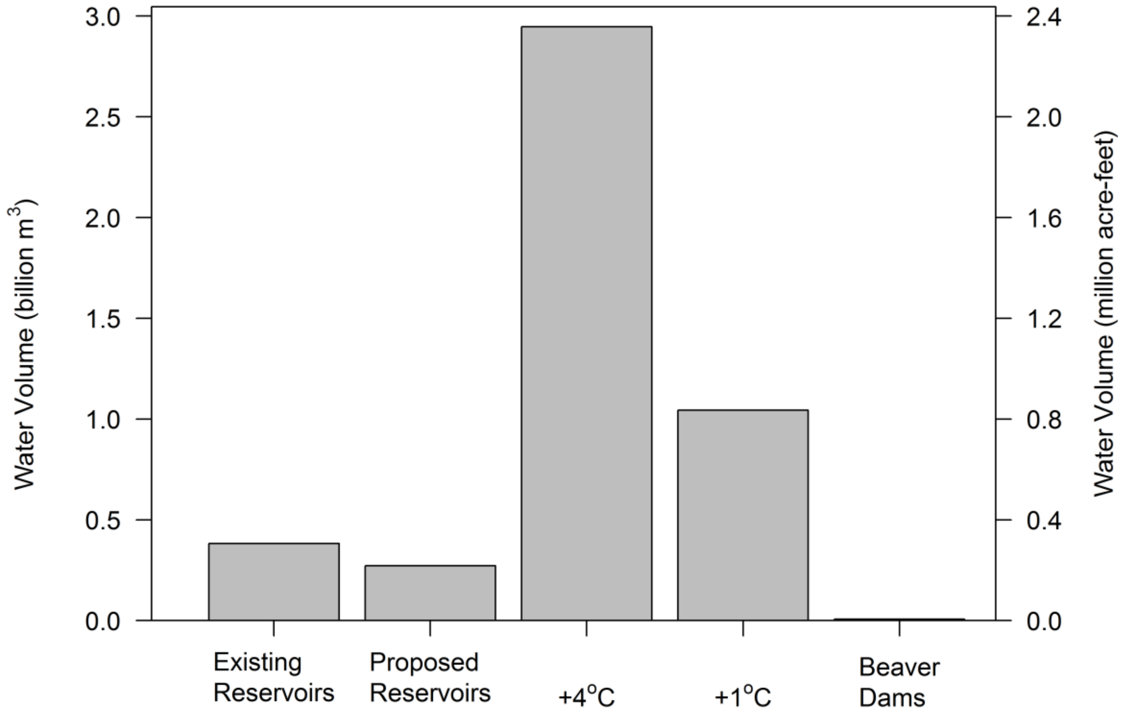


Figure 3.15. Total volume of water stored in existing reservoirs, potential storage from proposed reservoirs, and expected storage loss from snowpack under warming scenarios of 1 ˚C and 4 ˚C compared to the total storage beaver dams may provide with median dam heights at quasi 100% of maximum estimated capacity.

DISCUSSION

Using a combination of models and methods we produce spatial estimates of the water storage increases provided by beaver dams at 5%, 25%, 50%, and quasi 100% of maximum estimated riverscape capacity to support beaver dams. These estimates of water storage are not insubstantial with increases of up to 6.65 million m^3 for dams of median height at quasi 100% of maximum capacity. Beaver dam water storage increased only slightly from baseline conditions to 5% capacity, with greater increases coming between 5% and 50% capacity, and the greatest increases occurring after 50% of maximum capacity. For the state of Utah, current dam densities are estimated to be at around 8% of maximum capacity (the Little Bear – Logan River HU8 is at 18%), with some watersheds at capacities of less than 1%, indicating substantial potential to increase the number of beaver dams (Macfarlane *et al.*, 2014), and thus the amount of water storage, within valley bottoms. However, it is unrealistic to expect full dam capacity in any given watershed, or across a landscape, as resources require time to regenerate after exploitation by beaver, density dependent constraints on beaver populations may emerge, and conflict with humans (Macfarlane *et al.*, 2014) will likely prevent population expansion in some areas. Macfarlane et al. (2014) estimate the maximum attainable capacity of active beaver dams on a landscape to be around 50% of estimated maximum capacity, where some reaches are actively maintained by beaver while others recover from previous occupancy. In reaches once occupied, but abandoned (permanently or temporarily) hydrologic impacts of existing, inactive dams may still persist for decades if dams remain at least partially intact. In our analysis we have not subtracted the water storage provided by existing dams in the Bear River Basin, therefore, our water storage results indicate the maximum impact beaver dams may have on water storage. Also, maximum beaver dam capacity estimates were not adjusted to exclude areas where construction of beaver dams would be discouraged because of high conflict probability with humans.

We estimate groundwater to account for approximately two thirds of the water stored by beaver dams (Figure 3.9). While our validation of MODFLOW methods shows a relationship between our predicted groundwater levels and observed groundwater levels, the small sample size for groundwater validation at Curtis Creek and high variability at Bridge Creek (Figure 3.8) make it difficult to evaluate this relationship. Without pre-dam construction data at Bridge Creek, and no dam height measurements, we were left to make assumptions about dam height and the effect of breached dams on groundwater levels. These assumptions undoubtedly affect our ability to distinguish between error in groundwater modeling methods and noise in field data and model parameterization. Furthermore, changes to groundwater storage were modeled with nationally available 10 m DEMs. It was necessary to use these moderate resolution DEMs to make computation over our large study area tractable, and because higher resolution data were not available for the entirety of the Bear River Basin. One of the limitations when modeling at this large scale is the availability of high resolution topography, and, if such topography were available, the computational overhead required to analyze these data at such a broad spatial scale. Nevertheless, validation for Curtis Creek provided relatively good results, but suffered from a small number of wells over a small spatial extent, as do many groundwater studies. The estimated increases that beaver dams may contribute to underground reservoirs provides insight to mechanisms driving previous observations of increased stream base flow and stresses the need for additional data collection with the intent of better estimating and parameterizing groundwater changes associated with beaver dams.

From application of the Tennant et al. (2015b) framework for estimating declines in peak SWE, we show that the lost storage in snowpack in the Bear River basin could be substantial, with volumetric water loss of decreased peak SWE being greater than three times the existing reservoir storage in the Bear River Basin, under some scenarios. These results qualitatively compare to those presented by Klos et al. (2014), and paint the picture of rain dominated and mixed rain/snow precipitation regimes shifting to higher elevations as warming occurs (Figure 3.3, 3.12, 3.14). However, it is important to note that these are rough estimates based on data averaged over a decade. In reality changes to precipitation regimes will likely exhibit much more inter- and intra-annual variability. Furthermore, only a fraction of this lost snowpack would be converted to stream runoff. The percentage of snowpack that is converted to streamflow varies widely (generally, from 10% - 90%) depending on local soil properties and landscape characteristics (Lee *et al.*, 2005; Martinec and Rango, 1986). Thus, estimated volumetric SWE losses represent a maximum value and runoff losses to groundwater recharge and evapotranspiration would increase the percentage to which beaver might mitigate SWE loss in these scenarios. Even at the least extreme warming scenario of 1˚C, water storage from beaver dams at quasi 100% of maximum capacity was only able to account for 3% of expected storage loss from snowpack at the scale of an individual HU12 (Figure 3.12), indicating that it is not realistic to expect beaver dams to completely mitigate SWE losses due to warming temperatures. This is especially apparent when considering that during winter months the entire Bear River Basin is frequently completely covered by snow, but beaver dams are able to only store water in the valley bottoms which comprise 7.9% of the basin's area. When considering only the SWE loss that is expected in the basin's valley bottoms, water storage increases provided by beaver dams have the ability to store up to 100% of water lost to peak SWE decreases in some areas.

While the estimated amounts of water retention may be a small number in relation to the storage of human-made reservoirs and water resources management (Figure 3.15), this storage could be extremely important for maintaining riparian ecosystems and may substantially supplement base flow on low-order tributaries (Majerova *et al.*, 2015; Nyssen *et al.*, 2011; Puttock *et al.*, 2017). Increased storage on low-order, higher elevation tributaries may be extremely important as these sites generally occur upstream of human-made reservoirs (Figure 3.2) and such locations will be most susceptible to snowpack decreases as many are fed by snowmelt throughout the summer. Furthermore, if beaver dam water storage was comparable to expected SWE losses or human-made reservoir capacities, alterations to downstream water availability may result in legal action to protect the water rights of downstream users, potentially limiting implementation of beaver-related restoration actions, even those without hydrological goals. The relatively small storage capacities of beaver dams, coupled with their ability to affect a large percentage of valley-bottoms (Figure 3.13) may present a unique opportunity to improve riparian ecosystems and effect local hydrologic regimes without necessarily causing negative impacts for downstream water users.

Our modeling methods do not account for groundwater recharge resulting from new channels forced onto the floodplain by beaver dams. In some cases creation of such channels has been shown to have substantial effects on groundwater for hundreds of meters downstream of beaver dams (Westbrook *et al.*, 2006). Additionally, in partly confined, and laterally unconfined valley settings creation of floodplain channels and overbank flows may provide additional habitat for beaver colonies, increasing dam capacities (Westbrook *et al.*, 2011). Despite the limitations of 10 m topographic data, these are the highest resolution data available at large spatial scales in the western US, and while higher resolution data may provide more detailed results, we believe these 10 m data provide the most tractable means to achieve our objectives. Analyses from

Chapter 2 (herein) indicate that at the subwatershed (HU12) scale these data, combined with our modeling methods, are identifying the hydrologic signature of beaver dams. While we recognize the importance of overbank flows and creation of new channels as important factors contributing to water storage, modeling these features at a 10 m spatial resolution may not be appropriate, requiring additional investigation of the degree to which water storage is supplemented by these features and events and the variables driving them. Exclusion of overbank flows from our model suggests that our estimates of groundwater storage may be underrepresented. Beaver dams may also force greater hydraulic connectivity of streams to the floodplain at high flows, while these events do not provide sustained groundwater recharge throughout an entire year they may seasonally recharge large areas of shallow valley-bottom aquifers that may not be affected otherwise, further increasing water storage and altering the residence time of water travelling downstream. We also do not account for increased evapotranspiration which may result from increased areal coverage of water on the landscape and increased water availability to plants as groundwater tables rise. When coupled with soil information, estimates of groundwater elevation may provide opportunities to model changes to vegetation communities within valley bottom, presenting an opportunity to anticipate restoration potential (Macfarlane *et al.*, 2016) and changes to evapotranspiration rates. The degree to which evapotranspiration may be altered by beaver dam construction, and how such an alteration may (or may not) affect streamflow is also relatively unexplored.

The synergistic effects of these processes across multiple beaver dams along a stream or throughout a watershed could have unanticipated effects on flow regimes.

Though our storage estimates are orders of magnitude lower than the expected results of climate change, evidence from other studies has provided evidence that beaver dams significantly impact hydrologic regimes on streams. These studies have focused on quantifying the hydrologic effects of single dams, or dam complexes, and have not considered the cumulative impacts of multiple dam complexes along a waterway (Majerova *et al.*, 2015; Nyssen *et al.*, 2011; Puttock *et al.*, 2017). If effects observed at these dam complexes are cumulatively additive (not to mention interactive) throughout a stream network they could provide substantial impacts on the timing of water delivery. While our study shows that the total storage provided by beaver dams is only a small fraction of the total water budget of a large basin, it neglects to identify how the cumulative impacts of these dams may affect the timing of water delivery. A rainfall-runoff modeling approach is needed to fully understand the impacts of dam density in mitigating future climatic conditions and precipitation regimes.

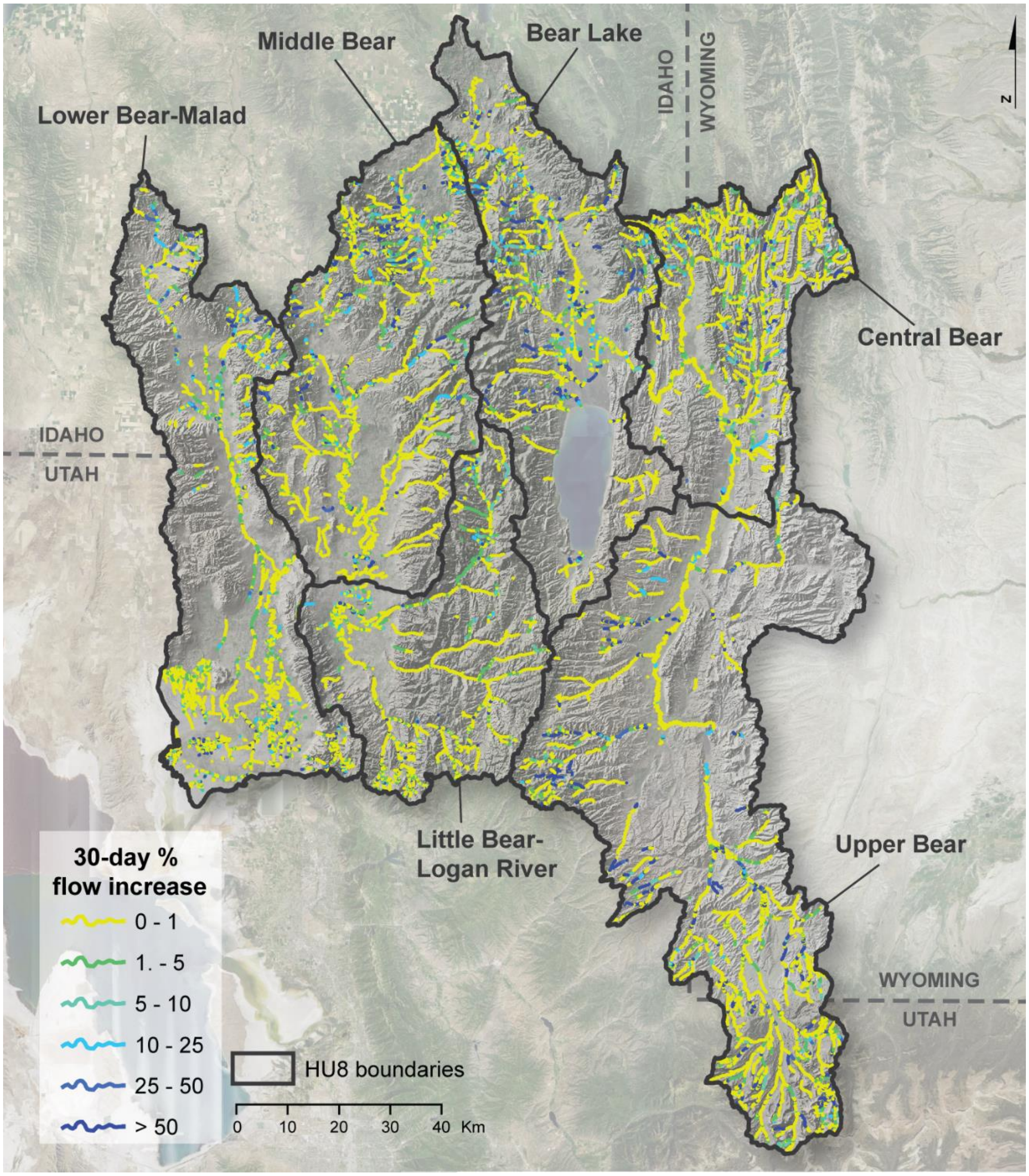


Figure 3.16. Maximum degree to which increased water storage from beaver dam construction may increase base flow over a 30 day period.

REFERENCES

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier, 2005. Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions. Nature 438:303–309, doi: 10.1038/nature04141.

Barrett, A.P., 2003. National Operational Hydrologic Remote Sensing Center Snow Data Assimilation System (SNODAS) Products at NSIDC. National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences.

Beedle, D.L., 1991. Physical Dimensions and Hydrologic Effects of Beaver Ponds on Kuiu Island in Southeast Alaska., http://ir.library.oregonstate.edu/xmlui/handle/1957/9343, *accessed* 1 Feb 2016.

Bowen Collins & Associates and HDR Engineering, 2014. Bear River Pipeline Concept Report., https://www.cachecounty.org/assets/department/water/brpipeline/Vol 1_Final_Bear River Pipeline Concept Rpt.pdf, *accessed* 5 Apr 2017.

Carroll, T., D. Cline, G. Fall, L. Li, and A. Nilsson, 2003. Seasonal Snow Cover Monitoring and Modeling for the Coterminous United States. EGS-AGU-EUG Joint Assembly., p. 1396.

Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier, and R.N. Palmer, 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climate Change 62:337–363, doi: 10.1023/B:CLIM.0000013684.13621.1f.

Collen, P. and R.J. Gibson, 2000. The General Ecology of Beavers (Castor Spp.), as Related to Their Influence on Stream Ecosystems and Riparian Habitats, and the Subsequent Effects on Fish - A Review. Reviews in Fish Biology and Fisheries 10:439–461, doi: 10.1023/A:1012262217012.

Cooke, H.A. and S. Zack, 2008. Influence of Beaver Dam Density on Riparian Areas and Riparian Birds in Shrubsteppe of Wyoming. Western North American Naturalist 68:365–373, doi: 10.3398/1527-0904(2008)68[365:IOBDDO]2.0.CO;2.

Cross, M.S., E.S. Zavaleta, D. Bachelet, M.L. Brooks, C.A.F. Enquist, E. Fleishman, L.J. Graumlich, C.R. Groves, L. Hannah, and L. Hansen, 2012. The Adaptation for Conservation Targets (ACT) Framework: A Tool for Incorporating Climate Change into Natural Resource Management. Environmental Management 50:341–351.

Dolan, E.J., 2010. Fur, Fortune, and Empire: The Epic History of the Fur Trade in Ameria. W. W. Norton & Company, New York, New York.

Evans, E., C.J. Volk, M. Nahorniak, J. Hall, N. Weber, N. Bouwes, J.M. Wheaton, C.E. Jordan, and P. M., Raising Groundwater Levels and Increaseing Surface-Groundwater Exchange with Beaver Dams in an Incised Desert Stream. Ecohydrology.

Feiner, K. and C.S. Lowry, 2015. Simulating the Effects of a Beaver Dam on Regional Groundwater Flow through a Wetland. Journal of Hydrology: Regional Studies 4:675–685.

Fredlake, M., 1997. Re-Establishment of North American Beaver (Castor Canadensis) into the San Pedro Riparian National Conservation Area. US Bureau of Land Management, Environmental Assessment EA No. AZ-060–97-004, Tucson, Arizona.

Fretwell, S.D., 1972. Populations in a Seasonal Environment. Princeton University Press.

Fretwell, S.D. and J.S. Calver, 1969. On Territorial Behavior and Other Factors Influencing Habitat Distribution in Birds. Acta Biotheoretica 19:37–44.

Fryirs, K.A., J.M. Wheaton, and G.J. Brierley, 2016. An Approach for Measuring Confinement and Assessing the Influence of Valley Setting on River Forms and Processes. Earth Surface Processes and Landforms.

Gibson, P.P. and J.D. Olden, 2014. Ecology, Management, and Conservation Implications of North American Beaver (Castor Canadensis) in Dryland Streams. Aquatic Conservation: Marine and Freshwater Ecosystems 24:391–409.

Gilbert, J.T., W.W. Macfarlane, and J.M. Wheaton, 2016. TheValley Bottom Extraction Tool (V-BET): A GIS Tool for Delineating Valley Bottoms across Entire Drainage Networks. Computers & Geosciences.

Gurnell, A.M., 1998. The Hydrogeomorphological Effects of Beaver Dam-Building Activity. Progress in Physical Geography 22:167–189, doi: 10.1177/030913339802200202.

Harbaugh, A.W., 2005. MODFLOW-2005, the US Geological Survey Modular Ground-Water Model: The Ground-Water Flow Process. US Department of the Interior, US Geological Survey Reston, VA, USA.

Hood, G.A. and S.E. Bayley, 2008. Beaver (Castor Canadensis) Mitigate the Effects of Climate on the Area of Open Water in Boreal Wetlands in Western Canada. Biological Conservation 141:556–567, doi: 10.1016/j.biocon.2007.12.003.

Johnston, C.A. and R.J. Naiman, 1990. The Use of a Geographic Information System to Analyze Long-Term Landscape Alteration by Beaver. Landscape Ecology 4:5–19.

Johnston, Naiman, C.A. Johnston, and R.J. Naiman, 1990. The Use of a Geographic Information System to Analyze Long-Term Landscape Alteration by Beaver. Landscape Ecology 4:5–19.

Jordan, R., 1991. A One-Dimensional Temperature Model for a Snow Cover: Technical Documentation for SNTHERM. 89. DTIC Document.

Karran, D.J., C.J. Westbrook, J.M. Wheaton, C.A. Johnston, and A. Bedard-Haughn, 2016. Rapid Surface Water Volume Estimations in Beaver Ponds. Hydrology and Earth System Sciences Discussions, doi: 10.5194/hess-2016-352.

Klos, P.Z., T.E. Link, and J.T. Abatzoglou, 2014. Extent of the Rain-Snow Transition Zone in the Western U.S. under Historic and Projected Climate. Geophysical Research Letters:n/a-n/a, doi: 10.1002/2014GL060500.

LANDFIRE, 2016. Existing Vegetation Type (EVT) Layer Landscape Fire and Resource Management Planning Tools Project. US Geological Survey, http://www.landfire.gov/NationalProductDescriptions21.php, *accessed* 1 Mar 2016.

Lee, S., A.G. Klein, and T.M. Over, 2005. A Comparison of MODIS and NOHRSC Snow-Cover Products for Simulating Streamflow Using the Snowmelt Runoff Model. Hydrological Processes 19:2951–2972.

Lokteff, R.L., B.B. Roper, and J.M. Wheaton, 2013. Do Beaver Dams Impede the Movement of Trout? Transactions of the American Fisheries Society 142:1114–1125, doi: 10.1080/00028487.2013.797497.

Lowry, M.M., 1993. Groundwater Elevations and Temperature Adjacent to a Beaver Pond in Central Oregon. Oregon State University, http://ir.library.oregonstate.edu/jspui/handle/1957/9566, *accessed* 18 Dec 2013.

Macfarlane, W.W., J.T. Gilbert, M.L. Jensen, J.D. Gilbert, N. Hough-Snee, P.A. McHugh, J.M. Wheaton, and S.N. Bennett, 2016. Riparian Vegetation as an Indicator of Riparian Condition: Detecting Departures from Historic Condition across the North American West. Journal of Environmental Management.

Macfarlane, W.W., J.M. Wheaton, N. Bouwes, M.L. Jensen, J.T. Gilbert, N. Hough-Snee, and J.A. Shivik, 2017. Modeling the Capacity of Riverscapes to Support Beaver Dams. Geomorphology 277:72–99.

Macfarlane, W.W., J.M. Wheaton, and M.L. Jensen, 2014. The Utah Beaver Restoration Assessment Tool : A Decision Support & Planning Tool.

Majerova, M., B.T. Neilson, N.M. Schmadel, J.M. Wheaton, and C.J. Snow, 2015. Impacts of Beaver Dams on Hydrologic and Temperature Regimes in a Mountain

Stream. Hydrology and Earth System Sciences 19:3541–3556, doi: 10.5194/hess-19-3541-2015.

Martinec, J. and A. Rango, 1986. Parameter Values for Snowmelt Runoff Modelling. Journal of Hydrology 84:197–219.

Naiman, R.J., C.A. Johnston, and J.C. Kelley, 1988. Alteration of North American Streams by Beaver. Bioscience 38:753–762, http://www.jstor.org/stable/pdfplus/1310784.pdf?acceptTC=true&acceptTC=true&jpdConfirm=true, *accessed* 18 Dec 2013.

Niswonger, R.G., S. Panday, and M. Ibaraki, 2011. MODFLOW-NWT, a Newton Formulation for MODFLOW-2005. US Geological Survey Techniques and Methods 6:A37.

Nobre, A.D., L.A. Cuartas, M. Hodnett, C.D. Rennó, G. Rodrigues, A. Silveira, M. Waterloo, and S. Saleska, 2011. Height Above the Nearest Drainage – a Hydrologically Relevant New Terrain Model. Journal of Hydrology 404:13–29, doi: 10.1016/j.jhydrol.2011.03.051.

Nyssen, J., J. Pontzeele, and P. Billi, 2011. Effect of Beaver Dams on the Hydrology of Small Mountain Streams: Example from the Chevral in the Ourthe Orientale Basin, Ardennes, Belgium. Journal of Hydrology 402:92–102, doi: 10.1016/j.jhydrol.2011.03.008.

Pollock, M.M., G.R. Pess, T.J. Beechie, and D.R. Montgomery, 2004. The Importance of Beaver Ponds to Coho Salmon Production in the Stillaguamish River Basin , Washington , USA. North American Journal of Fisheries Management 24:749–760, doi: 10.1577/M03-156.1.

Popescu, V.D. and J.P. Gibbs, 2009. Interactions between Climate, Beaver Activity, and Pond Occupancy by the Cold-Adapted Mink Frog in {New} {York} {State}, {USA}. Biological Conservation 142:2059–2068, doi: 10.1016/j.biocon.2009.04.001.

Portugal, E., J.M. Wheaton, and N. Bouwes, 2015a. Spring Creek Area Adaptive Beaver Management Plan. :25, doi: 10.13140/RG.2.1.2075.3361.

Portugal, E., J.M. Wheaton, K. Sorenson, M. Majerova, B. Hunt, and N. Bouwes, 2015b. Hardware Ranch Adaptive Beaver Management Plan. :26, https://www.researchgate.net/profile/Joseph_Wheaton/publication/309905727_Draft_-_Hardware_Ranch_Adaptive_Beaver_Management_Plan/links/5825ece808ae61258e4616f7.pdf, *accessed* 5 Apr 2017.

Puttock, A., A.M. Cunliffe, K. Anderson, and R.E. Brazier, 2015. Aerial Photography Collected with a Multirotor Drone Reveals Impact of Eurasian Beaver Reintroduction on Ecosystem Structure. Journal of Unmanned Vehicle Systems.

Puttock, A., H.A. Graham, A.M. Cunliffe, M. Elliott, and R.E. Brazier, 2017. Eurasian Beaver Activity Increases Water Storage, Attenuates Flow and Mitigates Diffuse Pollution from Intensively-Managed Grasslands. Science of The Total Environment 576:430–443.

Rosell, F., O. Bozsér, P. Collen, and H. Parker, 2005. Ecological Impact of Beavers Castor Fiber and Castor Canadensis and Their Ability to Modify Ecosystems. Mammal Review 35:248–276, doi: 10.1111/j.1365-2907.2005.00067.x.

Soil Survey Staff, Soil Survey Geographic (SSURGO) Database. Natural Resources Conservation Service, United States Department of Agriculture, https://sdmdataaccess.sc.egov.usda.gov/, *accessed* 1 Mar 2016.

Stevens, C., C. Paszkowski, and A. Foote, 2007. Beaver ({Castor} Canadensis) as a Surrogate Species for Conserving Anuran Amphibians on Boreal Streams in {Alberta}, {Canada}. Biological Conservation 134:1–13, doi: 10.1016/j.biocon.2006.07.017.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2004. Changes in Snowmelt Runoff Timing in Western North America Under a “Business As Usual” Climate Change Scenario. Climatic Change 62:217–232.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate 18:1136–1155, doi: 10.1175/JCLI3321.1.

Tennant, C.J., B.T. Crosby, and S.E. Godsey, 2015a. Elevation-dependent Responses of Streamflow to Climate Warming. Hydrological Processes 29:991–1001.

Tennant, C.J., B.T. Crosby, S.E. Godsey, R.W. VanKirk, and D.R. Derryberry, 2015b. A Simple Framework for Assessing the Sensitivity of Mountain Watersheds to Warming-driven Snowpack Loss. Geophysical Research Letters 42:2814–2822.

UDWR, 2010. Utah Beaver Management Plan 2010-2020. Salt Lake City, UT.

USACE, 2005. National Inventory of Dams, Water Control Infrastructure., https://nationalmap.gov/small_scale/mld/dams00x.html, *accessed* 20 Jan 2017.

USGS, 2016. National Hydrography Dataset. US Geological Survey, http://nhd.usgs.gov/, *accessed* 1 Mar 2016.

Westbrook, C.J., D.J. Cooper, and B.W. Baker, 2006. Beaver Dams and Overbank Floods Influence Groundwater-Surface Water Interactions of a Rocky Mountain Riparian Area. Water Resources Research 42:1–12, doi: 10.1029/2005WR004560.

Westbrook, C.J., D.J. Cooper, and B.W. Baker, 2011. Beaver Assisted River Valley Formation. River Research and Applications 27:247–256, doi: 10.1002/rra.1359.

Wieczorek, M.E., 2014. Area- and Depth-Weighted Averages of Selected SSURGO Variables for the Conterminous United States and District of Columbia.

Wilkowske, C.D., T.A. Kenney, and S.J. Wright, 2008. Methods for Estimating Monthly and Annual Streamflow Statistics at Ungaged Sites in Utah. US Department of the Interior, US Geological Survey.

Woo, M.-K. and J.M. Waddington, 1990. Effects of Beaver Dams on Subarctic Wetland Hydrology. Arctic 43:223–230, doi: 10.14430/arctic1615.

Wurtsbaugh, W., C. Miller, S. Null, P. Wilcock, M. Hahnenberger, and F. Howe, 2016. Impacts of Water Development on Great Salt Lake and the Wasatch Front.

CHAPTER 4

SIGNIFICANCE

Our primary purpose was to test the hypothesis that an increased number of beaver dams may be able to mitigate decreased water storage in snowpack anticipated under climate warming scenarios. To test this hypothesis, we needed a way to estimate how much water could be stored in beaver ponds as well as what degree of increase in valley-bottom groundwater storage beaver dams might induce. We collected detailed data from over 500 beaver dams in Utah, Idaho, and Oregon to supplement empirical data describing the height distributions of beaver dams and identify potential factors contributing to spatial differences in dam height. With these empirical data providing descriptions of beaver dam height distributions, we developed and validated the Beaver Dam Surface Water Estimation Algorithm (BD-SWEA), a predictive algorithm estimating the volume and spatial extent of a pond resulting from a beaver dam of a given height at a given location and takes a dam height distribution and DEM as inputs. We then estimated losses to peak SWE in the Bear River basin under warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C using the framework presented by Tennant et al. (2015) for assessing SWE loss at the watershed level. Potential surface water storage of beaver dams was estimated for the Bear River basin with BD-SWEA under beaver dam capacity scenarios of 5%, 25%, 50%, and quasi 100% of maximum dam capacity estimated with the Beaver Restoration Assessment Tool (BRAT), groundwater for these simulations was estimated by parameterizing MODFLOW (Harbaugh, 2005) with outputs from BD-SWEA to identify the potential effects of dams on groundwater tables.

Validation of BD-SWEA indicated that predictions of pond area are most accurate with higher resolution topographic data, but that nationally available 10 m DEMs may be adequate for modeling future scenarios at landscape scales. Estimates of pond volume produced from BD-SWEA produce a strong relationship with measured pond volumes with both 1 m and 10 m topographic data, supporting use of this simple model to predict beaver pond volumes across broad spatial scales. Results from MODFLOW simulations also indicate our methods for representing groundwater change follow the general trend of changes measured in the field, though the groundwater relationships calculated with MODFLOW were not as strong as the surface relationships calculated with BD-SWEA.

Application of the Tennant et al. (2015) methodology to estimate SWE loss within a watershed yielded reduction in maximum SWE by approximately 22%, 41%, 54%, and 63% under the warming scenarios of 1˚C, 2˚C, 3˚C, and 4˚C, respectively. These losses are substantial and simulated losses at an increase of 4˚C are nearly triple existing reservoir capacity in the basin. Under a warming scenario of 1˚C at quasi 100% of maximum estimated capacity, beaver dams provide enough storage to offset up to 3% of anticipated snowpack loss for specific HU12 watersheds. While the overall percentage of SWE loss that beaver have the potential to store is low, beaver dams provide storage higher in the watershed than proposed increases to human-made reservoir storage (Figure 3.14) and may thus have an important function in maintaining riparian ecosystems and supplementing late season base flow higher in watersheds. Methods for modeling groundwater also do not account for overbank flows which have the potential to greatly increase infiltration and the footprint of increased groundwater storage (Westbrook *et al.*, 2006), especially in partially confined and laterally unconfined valley settings. Therefore, our methods are likely underestimating total groundwater storage.

Our results seem to suggest that from a water resources and storage volume perspective, beaver dams really are just a ‘drop in the bucket’. However, this ‘drop’ could have significant implications for maintaining connectivity of aquatic systems. Along an elevational gradient, a large portion of water stored by beaver dams occurs higher in watersheds (Figure 3.14) on smaller order streams. Water storage in these headwater systems could be extremely important as SWE decreases are observed as their water source may not continue to be reliable through summer low flow periods, and seasonal drying of these streams could result in annual disconnection of aquatic systems. As flows in these streams are much smaller than higher-order tributaries and mainstem rivers, the small amounts of water storage created by beaver dams may be enough to sustain perennial flow and connectivity of riparian zones. At these high elevation locations human-made reservoirs (or other water retention structures) are often not practical as storage volumes are limited by annual water quantities and environmental law prohibits, or complicates, activities with environmental impacts as many of these high elevation areas are public land and/or designated wilderness areas. Therefore, to address increased variability of hydrologic regimes and maintain connectivity in many these systems a natural approach may be required.

From a legal perspective, if beaver dams stored vast amounts of water, litigation may be brought forth by downstream water users if the quantity or timing of flows were measurably changed. Such litigation could easily thwart beaver-based restoration strategies that have proved extremely effective in some areas, even if the restoration did not have a hydrologic purpose. Questions will likely arise as to what constitutes a ‘measurable change’ and the initial conditions from which this change occurs. Is a measurable change defined by conditions at the time a law or precedent was set forth, the previous year, an average over a certain period of time, expected future conditions, or some other definition? When our estimated magnitude of potential changes from beaver dams is compared with potential shifts in hydrological regimes it becomes apparent that at large scales it will become increasingly difficult to disentangle any effects beaver dams may have on hydrologic regimes from larger scale climatic patterns. While it is somewhat disappointing that our results do not suggest beaver have the potential to significantly alter hydrologic regimes, it is also reassuring that these small hydrologic changes will make it more difficult to halt implementation of beaver-based restoration.

While we do provide a large-scale study quantifying the degree to which beaver may buffer water storage lost from decreasing snowpack, we do not assess the effect beaver dams may have on timing of runoff. While our results may suggest that increases to water storage from increased beaver dams are negligible in the context of water resources management and snowpack, they could be very significant locally. The results do not begin to explore how critically important changing the residence time distribution of water will be and the implications of doing this throughout a drainage network. The cumulative effects of beaver dams and beaver dam complexes along a stream or within a watershed and their associated water storage may produce nonlinear effects as the number of dams increases, altering the delivery of water downstream. Whether this alteration to water delivery results in a significant or in-detectable impact on total runoff is worthy of much more consideration. However, we speculate that the impact may be more pronounced on the timing and delivery of water, which may be far more meaningful than increases or decreases to total runoff. We stress that further research into this matter is necessary before we can fully understand the degree to which beaver may be able to offset anticipated climatic changes. We also show that BD-SWEA, coupled with BRAT and MODFLOW, provides a framework for assessing hydrologic impacts of beaver dams across broad scales under various scenarios. As the hydrologic changes associated with beaver dams have been shown by others to be desirable in many instances (Gibson and Olden, 2014; Hood and Bayley, 2008; Nyssen *et al.*, 2011; Stout *et al.*, 2016), application of these tools will allow natural resource managers the ability to assess where and how restoration of beaver may provide the greatest benefits to meet restoration objectives.

REFERENCES

Gibson, P.P. and J.D. Olden, 2014. Ecology, Management, and Conservation Implications of North American Beaver (Castor Canadensis) in Dryland Streams. Aquatic Conservation: Marine and Freshwater Ecosystems 24:391–409.

Harbaugh, A.W., 2005. MODFLOW-2005, the US Geological Survey Modular Ground-Water Model: The Ground-Water Flow Process. US Department of the Interior, US Geological Survey Reston, VA, USA.

Hood, G.A. and S.E. Bayley, 2008. Beaver (Castor Canadensis) Mitigate the Effects of Climate on the Area of Open Water in Boreal Wetlands in Western Canada. Biological Conservation 141:556–567, doi: 10.1016/j.biocon.2007.12.003.

Nyssen, J., J. Pontzeele, and P. Billi, 2011. Effect of Beaver Dams on the Hydrology of Small Mountain Streams: Example from the Chevral in the Ourthe Orientale Basin, Ardennes, Belgium. Journal of Hydrology 402:92–102, doi: 10.1016/j.jhydrol.2011.03.008.

Stout, T.L., M. Majerova, and B.T. Neilson, 2016. Impacts of Beaver Dams on Channel Hydraulics and Substrate Characteristics in a Mountain Stream. Ecohydrology.

Westbrook, C.J., D.J. Cooper, and B.W. Baker, 2006. Beaver Dams and Overbank Floods Influence Groundwater-Surface Water Interactions of a Rocky Mountain Riparian Area. Water Resources Research 42:1–12, doi: 10.1029/2005WR004560.