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Modeling the surface storage potential of beaver dams in the Temple Fork Watershed

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Introduction

By building dams to alter their environment and thus increase their survival, North American Beaver (*Castor canadensis*) have earned the title of 'ecosystem engineer' (Wright et al. 2002). Beaver build dams to create the conditions necessary to evade predators, survive winter, and store food. When building dams, beaver remove vegetation and insert channel obstructions that alter the flow of water, thus the effects of beaver dams extend far beyond survival of beaver to influence many geomorphic, ecological and hydrological processes (Rosell et al. 2005, Pollock et al. 2014).

Hydrologically, the most obvious aspects of a beaver dam are its ability to store water (both in the pond itself, and by raising the adjacent groundwater table), attenuate floods, and increase evapotranspiration (Woo and Waddington 1990, Butler and Malanson 2005). For example, construction of a beaver dam creates a pond immediately upstream of the dam, effectively raising the water surface elevation for the entire pond extent, and can cause a stream to overflow its banks (Gurnell 1998). The raised water surface also raises the adjacent groundwater table, with the pressure head and overland flow created by the dam influencing surface and groundwater levels for hundreds of meters downstream (Westbrook et al. 2006). This increased storage can attenuate floods and increase the time required for water to exit a watershed (Burns and McDonnell 1998). Increases in the water table elevation and areal extent of surface water also makes water more available to plants (and the sun) and can serve to increase water loss through evapotranspiration (Woo and Waddington 1990).

Increased water storage and residence time in headwater catchments could be of great importance as current climatic trends and predictions for the intermountain west suggest shifts toward earlier spring snowmelt and a greater proportion of precipitation being delivered as rain (Stewart et al. 2005, Knowles et al. 2006, Mote 2006). The consequence of such trends is reduced storage in high elevation snowpack resulting in summer and autumn water shortages. In some localities these effects are already being observed, and are expected to become more apparent and severe throughout the entire region (Stewart et al. 2004, 2005). Some evidence suggests that beaver dams have the ability to increase water storage and base flows at local scales, but the cumulative effect of multiple dam complexes within a watershed has not yet been explored in detail (Westbrook et al. 2006, Hood and Bayley 2008, Nyssen et al. 2011). Until recently studies examining the effect of increasing dam density across a landscape have been precluded by lack of a predictive model from which to infer dam density (Macfarlane et al. In Press).

Development of the Beaver Restoration Assessment Tool (BRAT), a model that predicts the beaver dam capacity of a stream reach, by Macfarlane et al. (in press) has provided some of the necessary information to scale up, and test, the potential impacts of beaver dams on water storage and streamflow in a watershed. Using dam density estimates from the BRAT model may facilitate modeling of beaver dam processes at larger scales, which will allow quantification of the hydrological effects of beaver dams at scales meaningful to water management. When combined with nationally available geographic datasets there is potential to identify the possible regional impacts of beaver dams. I use existing digital elevation models (DEMs) to develop a model describing the surface storage potential of a beaver dam, then use the BRAT estimates and empirical beaver dam height data to determine surface water storage and residence time under different dam densities in a Northern Utah watershed.

Objectives

1. Develop a model describing the surface storage of a beaver dam.
2. Quantify changes in water storage and residence time under different dam density scenarios at the watershed scale using beaver dam capacity estimates from the BRAT model.
3. Identify the effects of data resolution on model results.

Methods

The Temple Fork Watershed is located in Northern Utah near the town of Logan (Figure 1). The watershed drains 41 km^2 and elevations range from 1755 – 2750 m with a mean of 2250 m. The stream network is comprised mainly of two perennial streams, Temple Fork and Spawn Creek. No permanent gaging stations exist, but the USGS StreamStats application (USGS 2015) estimates mean annual flow for Temple Fork at 0.47 m^3/s.

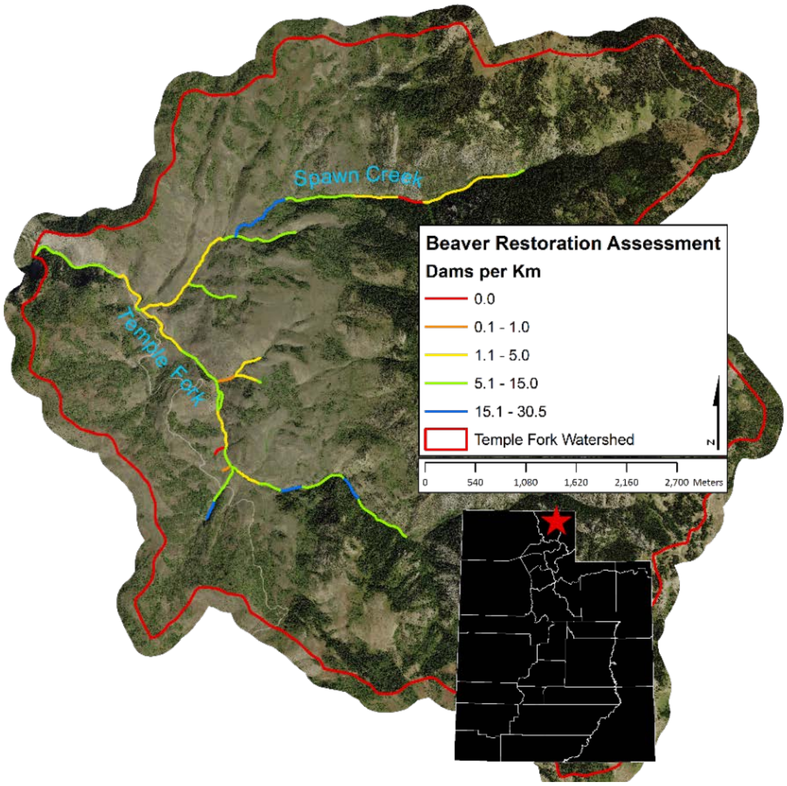

Figure 1. Location of the Temple Fork Watershed with beaver dam capacity estimates from the BRAT model for Temple Fork and Spawn Creek.

To obtain a baseline for the area inundated by beaver ponds in the Temple Fork Watershed, I digitized the extent of all ponds visible on the Google Earth (2015) imagery of October 7, 2014, and the location of the dam forming each pond. Dam points were snapped and joined to the BRAT line output to maintain spatial and methodological consistency between validation of existing ponds and scenario based simulations. The BRAT model determines the capacity of beaver dams that can be supported by a given stream segment (~250 m), relying primarily on stream power and near-stream vegetation (Macfarlane et al. in press). The result of the BRAT model is a multiline shapefile, congruent with the National Hydrography Dataset (NHD) flowlines, which contains dam capacity estimates for each reach under current and historical vegetation conditions and other reach properties such as vegetation type, slope, and stream power. At each point representing a beaver dam I modeled the inundation extent of the pond formed by a beaver dam.

Theoretically, the inundation extent of a beaver dam can be explained as

$$d = \frac{h}{s}$$

where d is the distance upstream the dam will cause inundation, h is the height of the dam, and s is the slope of the stream reach (Figure 2A). Assuming a beaver dam can be represented by a half cone the volume of pond can then be approximated by

$$V = \frac{1}{6}\pi d^2$$

where V is volume. Using DEMs this approximation can be improved by identifying the possible inundation extent of a dam and subtracting the ground surface elevation from the dam elevation (ground surface elevation + h). Positive values represent water depth and values less than or equal to zero represent dry ground. To find the maximum inundation extent created by a beaver dam I used d to create a search polygon that rotates 180˚ around the dam point in the upstream direction (Figure 2B). Then I calculated the actual inundation extent by subtracting ground surface elevations from the water surface elevation of the beaver dam, as explained above. I modeled pond inundation extents with DEMs from two different sources: the National Elevation Dataset (NED) one-third arc second (~8.92 m, hereafter referred to as 10 m) grids (U.S. Geological Survey 2009) and a 1 meter Light Detection and Ranging (LiDAR) dataset available for the Temple Fork Watershed (Lokteff 2011).

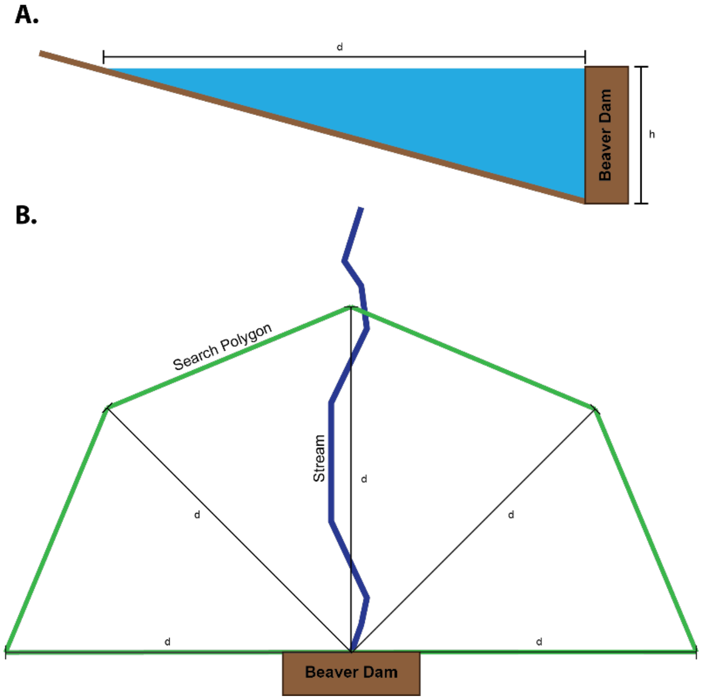

Figure 2. A) Simple cross section of a beaver pond indicating the upstream inundation extent (d). B) Example of the search polygons used to identify the maximum area of inundation for a dam at a given site.

Using the above method, the modeled area and volume of a beaver pond depend on local topography, and beaver dam height. I used DEMs to represent local topography, though DEMs contain error they are widely used to represent topography in models. Beaver dam heights, on the other hand, exhibit high variability and data explaining this variability are scarce. To account for stochasticity in beaver dam height I used Monte Carlo simulations (Manly 2006) to model the probability of a DEM cell being inundated. Each modeled scenario consisted of 1000 simulations, during each simulation the height of every beaver dam was randomly selected from a lognormal distribution (mean = -0.99, sd = 0.42; Figure 3) fitted to a distribution of height measurements (n=20, mean=0.98, sd=0.41) from the Temple Fork Watershed (Lokteff et al. 2013). After each simulation a new raster grid was created where inundated DEM cells were given a value of 1 and dry cells a value of 0. The result of this binary grid was then added to a cumulative grid, thus tracking the number of times a given grid cell was inundated during the 1000 simulations, and represents probability of inundation multiplied by 1000. I tabulated the inundation area for each probability of inundation and identified the probability which represented the area closest to the digitized area of beaver pond inundation in the watershed (Figure 4), then applied that probability to model volume and area of beaver ponds under different scenarios (Table 1, Figure 6).

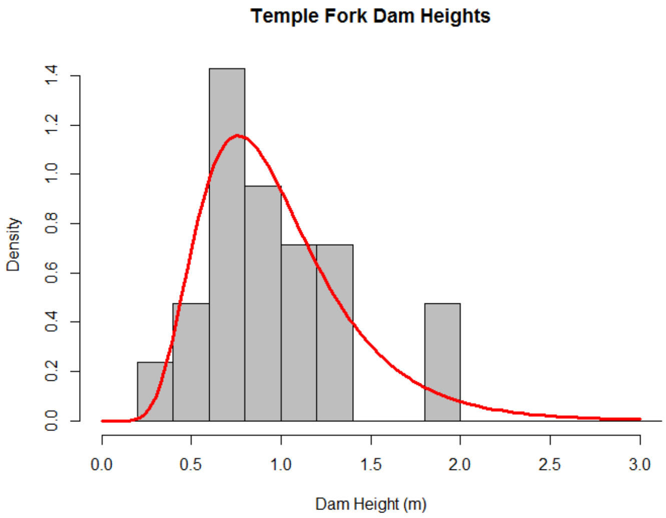

Figure 3. Histogram of the dam height distribution obtained by Loktеff et a. (2013) for the Temple Fork Watershed with the fitted lognormal distribution.

Using the BRAT outputs I modeled pond area and volume at 50% and 100% of estimated dam capacity. The number of dams on a given segment was calculated from BRAT capacity estimates, and modeled dam points were spaced evenly along the segment. Since the NHD flowlines are derived from different sources than the elevation datasets used in this model, it was necessary to adjust dam position to place dams at the lowest point in the channel. This was accomplished by sampling the DEM perpendicular to the flowline and identifying the minimum value along this transect. A beaver dam was modeled at the point corresponding to the center of the DEM cell with this minimum value. The entirety of this model was programmed in C++ and the Geospatial Data Abstraction Library (GDAL) version 1.11 (GDAL 2014) was used for representation of geographic data. As this research is ongoing, and the model is still under development, the code is not currently available. However, a preliminary version of the model written in python can be obtained at https://github.com/khafen74/beaver-dam-py.

Table 1. Areal coverage and volume of beaver ponds under existing, and two predicted conditions. Area and volume are cumulative values for the entire Temple Fork Watershed. RT Mean, RT Peak, and RT Low are residence time at mean annual flow (0.47 m^3/s), mean annual peak flow (1.06 m^3/s), and summer low flow (0.31 m^3/s; 80% exceedance probability in August), respectively.

Dam Capacity	Ponds	Area (m^2)	Mean Pond Area (m^2)	Volume (m^3)	RT Mean (hours)	RT Peak (hours)	RT Low (hours)
Digitized Existing (2014)*	35	5194.9	144.3	-	-	-	-
Existing (1m)	43	5198.0	120.9	2410.2	1.42	0.63	2.16
Existing (10m)	35	5193.7	198.9	2258.1	1.33	0.59	2.02
BRAT 50% (1m)	50	5374.0	103.3	2326.8	1.38	0.61	2.08
BRAT 50% (10m)	37	7830.5	206.8	2470.5	1.46	0.65	2.21
BRAT 100% (1m)	86	14288.0	106.6	6153.1	3.64	1.61	5.51
BRAT 100% (10m)	134	17658.7	204.5	4714.1	2.79	1.24	4.22

*Extents of these ponds were manually digitized form aerial imagery, therefore pond volumes are not available. All other values are model results.

Results

With the above methods I modeled the area of existing beaver ponds in the Temple Fork Watershed using DEMs of two different resolutions (1 m and 10 m) by identifying the probability of inundation corresponding to observed pond areas (Figure 4, Figure 5). Probabilities of inundation corresponding to observed pond areas were 0.47 and 0.58 for the 1 m and 10 m data, respectively (Figure 4). The 35 existing ponds covered 5194.9 m^2 of the watershed and had an average area of 144.3 m^2.

As would be expected, total pond area, total volume stored, and residence time increased as the number of beaver dams in the watershed increased (Table 1). The current number of beaver dams in the watershed is close to 50% of the carrying capacity predicted by BRAT, so only small changes are observed between current pond metrics and 50% capacity estimates. Hence the area, volume, and residence time shown for the 50% estimates are likely reflective of current conditions. Doubling the number of dams (100% capacity) resulted in an increase of total pond area from 5374.0 m^2 to 14288.0 m^2 (1 m) and 7830.5 m^2 to 17658.7 m^2 (10 m). An approximately two-fold increase in storage volume and residence time was also observed for both DEM resolutions (Table 1).

Differences in volume and area estimates are apparent between the 1 m and 10 m data. For both the 50% and 100% capacity estimate calculations a greater area of inundation was predicted from the 10 m DEM than the 1 m DEM. Volume was inversely related to cell resolution with the 1 m data yielding larger volume estimates than the 1 m data.

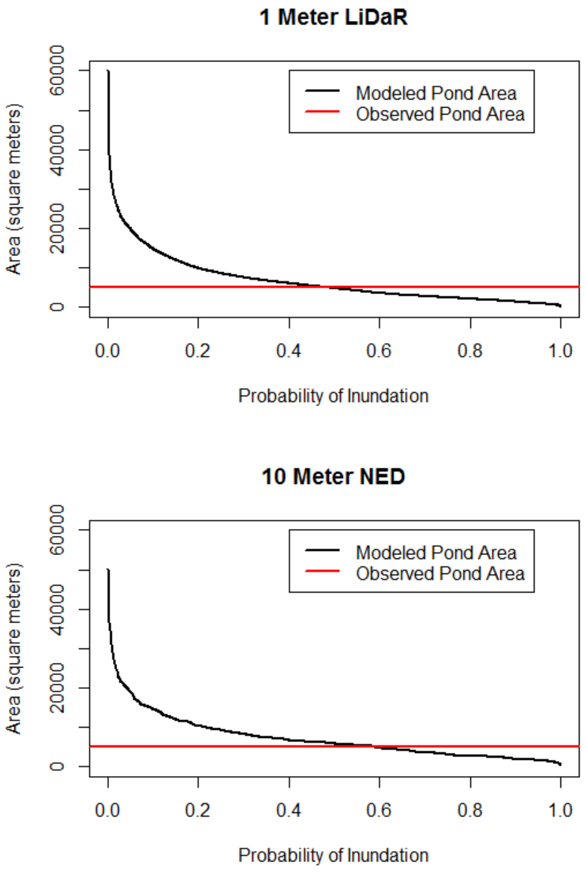

Figure 4. Relationship between inundated area and probability of inundation for the NED and LiDAR datasets. The red line displays the existing pond area as obtained from aerial imagery.

Discussion

This model is an important starting point for quantifying the effect beaver ponds may have on hydrologic processes under a changing climatic regime. However, more development and parameterization is necessary before it can be reliably applied at wide spatial scales. I parameterized the model with the distribution from a small sample of dams taken from a localized area, for the model to be applied at a larger spatial scale a more extensive sampling of beaver dam heights is required. It may even be necessary to describe beaver dam heights by watershed, or include a stream reach parameterization based on variables such as slope, confinement, and vegetation. The threshold probability of inundation is also relevant to only the Temple Fork Watershed, and should be tested against known pond areas in other watersheds to identify a more representative probability that could be applied across a landscape. However, the probability of inundation I determined for both the 1 m and 10 m DEMs (0.47 and 0.58, respectively) is near the median of the probability distribution. This probability value is representative of dam height and a value near the median indicates beaver dam height may vary randomly and Monte Carlo simulations may thus be a robust method for determining inundation extent.

Variability in the number of ponds, pond area, and pond volume between 1 m and 10 m datasets highlights the effect of data resolution on model outputs. Though the same number of dams were modeled for each simulation, the model predicted more ponds when using the 1 m data, and these ponds had a smaller average area than existing ponds, or ponds modeled with 10 m data. This is an artifact of how individual ponds are identified. My pond identification algorithm identifies groups of inundated cells, not necessarily every inundated cell within a specific search polygon. Since the model represents dams as a straight line, and the 1 m LiDAR data is of fine enough resolution to represent some active-channel topographic features, many modeled ponds are broken up by areas of higher elevation, resulting in multiple groups of inundated cells for one pond feature (Figure 5). In contrast, model predictions from the 10 m NED data exhibit greater total, and average pond area than was observed from existing ponds. This can be attributed to the coarseness (relative to the scale of a beaver pond) of the data. One pixel from the NED dataset represents 89.6 m^2, and the observed average pond area was 144.3 m^2. Therefore, one inundated pixel from the NED dataset represents about 50% of the actual average pond area. Including one extra inundated pixel when modeling ponds, or modeling a pond with an area smaller than the pixel area will thus serve to increase the mean and total pond area.

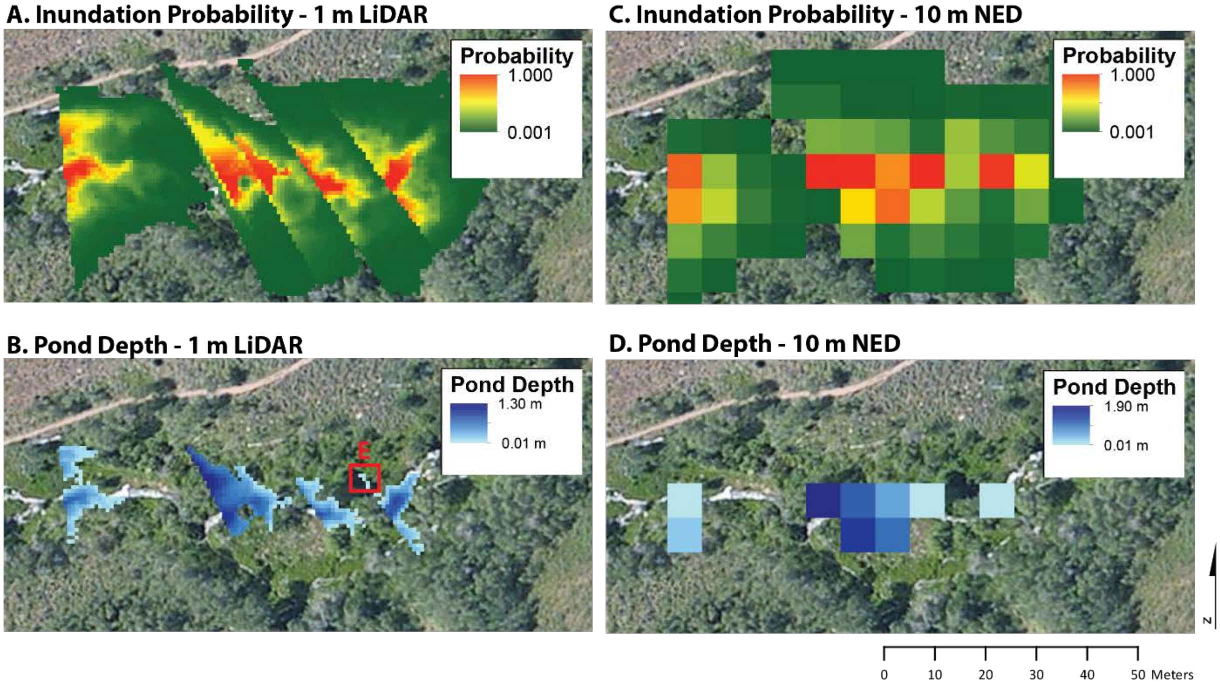

Figure 5. Inundation probability and pond depth as determined by the model for both the NED and LiDAR data. E highlights a small pond that was isolated from the main pond by topographic features. Though calculated from the same search polygon as the larger pond it was classified separately during analysis because it is not attached.

Though residence time is expected to increase as the number of beaver ponds on the landscape increases, the calculated result is likely insignificant in the context of climate change. I predicted an increase of about 3.5 hours (from 2.2 hours to 5.5 hours) in residence time for the Temple Fork Watershed under summer low-flow conditions (Table 1). However, I calculated residence time based on discharge estimates at the mouth of Temple Fork (USGS 2015). Since the majority of beaver dams occur on Spawn Creek, and on Temple Fork upstream of its confluence with Spawn Creek, the discharge I used to calculate residence time exceeds the actual discharge experienced by most beaver dams in the system. Therefore, to accurately estimate the effect beaver ponds have on residence time discharge estimates at a finer spatial scale are required. Furthermore, this model provides no quantification for changes in groundwater storage and residence time, which could easily dwarf the changes observed on the surface.

A. Existing ponds, digitized and modeled

B. Ponds at 50% of BRAT capacity estimate

C. Ponds at 100% of BRAT capacity estimate

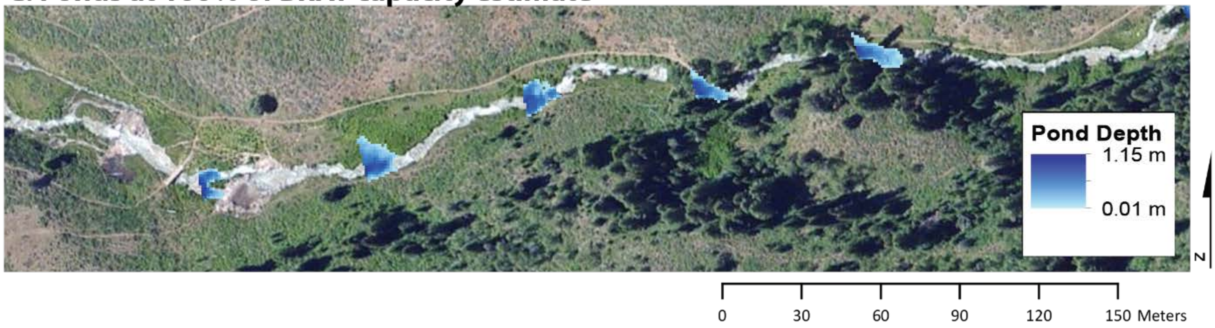

Figure 6. A) Digitized and modeled extents of existing ponds for a reach on Temple Fork. B) Modeled ponds at 50% of the BRAT capacity estimate. C) Modeled ponds at 100% of the BRAT capacity estimate. Actual extents were digitized from Google Earth Imagery (2014), and ponds were modeled with a 1 m LiDAR derived DEM.

Conclusion

To predict the potential storage provided by beaver dams in the Temple Fork Watershed I applied a simple physical model, and implemented Monte Carlo simulations to account for stochasticity in beaver dam height. Residence time calculations indicate that beaver ponds do increase the residence time of water traveling through a stream system, however to understand their complete effect residence time must be calculated at spatial scales smaller than that of a watershed outlet. The effect of spatial resolution is also an important variable to consider, and its effect may substantially affect model results in some cases. Overall, this study provides a starting point, and methods to build upon, for understanding the hydrologic effects of beaver dams at larger spatial scales.

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