Received: 30 August 2017 | Revised: 5 April 2018 | Accepted: 17 May 2018
DOI: 10.1002/eco.1993

RESEARCH ARTICLE

WILEY

Using remote sensing to assess the impact of beaver damming on riparian evapotranspiration in an arid landscape

Emily Fairfax | **Eric E. Small**

Department of Geological Sciences, University of Colorado Boulder, Boulder, Colorado, United States of America

Correspondence
Emily Fairfax, Department of Geological Sciences, University of Colorado Boulder, Boulder, CO 80309.
Email: emily.fairfax@colorado.edu

Funding information
Geological Society of America Graduate Research Grant; Birkeland Graduate Scholarship; National Defense Science & Engineering Graduate Fellowship (NDSEG) Program

Abstract

Beaver damming creates and maintains riparian ecosystems in arid regions, which are often afflicted by seasonal and multi-year droughts. We hypothesize that beaver ponds act as buffers against the effects of drought on nearby riparian vegetation via the following mechanism: Beaver ponds formed upstream of each dam retain water during wetter parts of the year, then during drier parts of the year, they gradually release that water into nearby soil where it is accessible to the roots of riparian vegetation. We calculated the evapotranspiration (ET) and normalized difference vegetation index (NDVI) of riparian vegetation on Susie and Maggie Creeks in northeastern Nevada from 2013 to 2016 and then compared the ET and NDVI to the location and intensity of beaver damming on the creeks. We found that the ET of riparian areas with beaver damming was 50–150% higher than the ET in riparian areas without beaver damming and that NDVI in dammed riparian areas was 6–88% higher than that in undammed areas. These differences peaked in mid-summer when the landscape is at its hottest and driest state. There was no apparent loss of beaver pond drought buffering as a multi-year drought (2013–2015) progressed. Our results indicate that riparian areas with beaver damming in arid landscapes are better able to maintain vegetation productivity than areas without beaver damming during both short and extended periods of drought.

KEYWORDS
arid, beaver, drought, evapotranspiration, METRIC, NDVI, remote sensing, riparian

1 | INTRODUCTION

1.1 | Beaver damming in arid landscapes

Through their construction of numerous dams, beavers create and maintain riparian ecosystems throughout the American west (Naiman, Melillo, & Hobbie, 1986; Pollock et al., 2014; Rosell, Bozser, Collen, & Parker, 2005)—including in desert climates (Andersen & Shafroth, 2010; Carillo, Bergman, Taylor, Nolte, & Viehoever, 2009; Gibson & Olden, 2014; Gibson, Olden, & O'Neill, 2015). The hydrologic and geomorphic structure of these beaver-dammed riparian areas differs significantly from undammed riparian areas (Green & Westbrook, 2009; Janzen & Westbrook, 2011; Pollock, Beechie, & Jordan, 2007). Beaver dams create deep ponds, which store large volumes of water on the surface and in the subsurface, and they help connect incised streams back to their floodplains (Karran, Westbrook, Wheaton, Johnston, & Bedard-Haughn, 2016; Lautz, Siegel, & Bauer, 2006; Levine & Meyer, 2014; Pollock, Castro, Jordan, Lewallen, & Woodruff, 2015; Polvi & Wohl, 2012). Furthermore, beaver ponds provide the hydrologic benefit of buffering peak flows and flood waves (Burns & McDonnell, 1998; Butler & Malanson, 2005; Hillman, 1998; Rosell et al., 2005). In this paper, we investigate another possible, less studied hydrologic benefit of beaver damming: drought buffering. For the purpose of this study, drought buffering refers to the ability for vegetation to produce a typical season arc in evapotranspiration (ET) similar to that predicted by the Penman–Monteith equation for potential evapotranspiration (PET; Allen, Pereira, Raes, & Smith, 1998) and avoid senescence despite little to no precipitation. For example, vegetation that is well-buffered against droughts would have a transpiration signal more similar to irrigated crops than to more precipitation-dependent vegetation in the landscape.

To buffer flood waves, beaver dams slow down and store large volumes of rapidly incoming water over a large area and then gradually release it over a period of days-to-months. Our proposed mechanism of beaver-dam-induced drought buffering is very similar to the mechanism behind beaver-dam-induced flood buffering: beaver ponds formed upstream of each dam retain water during wetter periods and then release it gradually over drier ones. Because beaver ponds have been shown to locally elevate the water table (Lowry, 1993; Westbrook, Cooper, & Baker, 2006), any pond water that enters the banks will flow both vertically and laterally along the phreatic surface and out into the broader riparian zone (Briggs, Lautz, Hare, & González-Pinzón, 2013; Jin, Siegel, Lautz, & Otz, 2009). Here, the pond water is accessible to the roots of riparian vegetation, acting similar to a subsurface irrigation system (Gurnell, 1998; Hammerson, 1994).

Given that productive plants are foundational to the trophic webs of most terrestrial ecosystems and that riparian zones are the main source of wetland habitat in arid and semi-arid landscapes (Kauffman, Beschta, Otting, & Lytjen, 1997; Knopf, Johnson, Rich, Samson, & Szaro, 1988; Macfarlane et al., 2016; Naiman, Pollock, & Decamps, 1993; Pettorelli et al., 2005), creating and preserving patches of consistently productive vegetation is crucial to wetland conservation efforts. However, due to their strong dependence on water availability, riparian ecosystems in general are particularly sensitive to droughts (Kauffman et al., 1997; Knopf et al., 1988). The relationship between riparian restoration and drought buffering was recently assessed at a location with beavers (Huntington et al., 2016), but the role that beaver damming plays and how strong of an influence it has on riparian ET and plant productivity has not been studied in depth. We hypothesize that beaver-dammed riparian ecosystems are better buffered against droughts than riparian areas without beaver activity. To test this hypothesis, we compared the ET and greenness of riparian vegetation—two indicators of plant productivity—along creeks with differing levels of beaver damming during both seasonal and multi-year droughts. If beaver-dammed riparian areas are better buffered against droughts than areas without beavers, then the promotion of beaver dam building activity should be considered in management plans for riparian areas in arid and semi-arid landscapes.

1.2 | Assessing vegetation productivity: ET and NDVI

Modelled ET and satellite-derived normalized difference vegetation index (NDVI) are used in this study to estimate the density and vigour of vegetation across the landscape. These indicators can then be interpreted as an approximation of the overall productivity of the riparian ecosystem (Carlson & Ripley, 1997; Fisher, Whittaker, & Malhi, 2011; Pettorelli et al., 2005). ET is the combination of evaporation of water directly from soil, water, and plant surfaces and transpiration by plants and, in general, correlates to greater species richness (Hawkins et al., 2003). Although both evaporation and transpiration are dynamic, we assume that the changes in the evaporation component of ET are relatively consistent over a given landscape. We believe this assumption is valid considering the main variables driving evaporation—incoming radiation, temperature, wind speed, and relative humidity—do not vary significantly on the spatial scale of this study. If changes in evaporation are consistent across the entire landscape, then relative spatial or temporal changes in the ET signal between any two areas will be primarily due to changes in plant transpiration. During the growing season, ET values close to the maximum PET indicate that plants are transpiring at their maximum potential rate. ET values less than the PET indicate that plant growth is being limited by something—typically lack water in semi-arid and arid landscapes (Laio, Porporato, Fernadnez-Illescas, & Rodriguez-Iturbe, 2001; Porporato, Laio, Ridolfi, & Rodriguez-Iturbe, 2001). If water-stress is extended, plants may undergo senescence—the strategic die off of plant tissue and slowing of growth rates designed to increase likelihood of long-term survival (Munné-Bosch & Alegre, 2004). NDVI is an indicator of photosynthetic activity by plants (Carlson & Ripley, 1997) and, when used in conjunction with ET, can distinguish high ET signals due to increased plant transpiration from high ET signals due to open water or soil evaporation.

NDVI is calculated directly from remotely sensed surface reflectance data (such as from the Landsat satellites; Tucker, 1979). ET is estimated using a combination of remote sensing and modelling. We used Landsat acquired images for the remote sensing portion, and for the model, we used the mapping evapotranspiration at high resolution with internalized calibration (METRIC) model (Allen, Tasumi, & Trezza, 2007). METRIC combines Landsat satellite imagery and local or modelled meteorological data to calculate the ET of a landscape. METRIC has been previously validated with field observations (Allen et al., 2007; Allen, Tasumi, Morse, & Trezza, 2005; French, Hunsaker, & Thorp, 2015; Paço et al., 2014) and has also been used without ground-based validation (Santos, Lorite, Allen, & Tasumi, 2012; Trezza, Allen, & Tasumi, 2013). A recent study by Liebert et al. used both modelled data from METRIC and ground-based eddy flux tower data to estimate the ET and a vegetation index of broad riparian areas in south-east Nevada, which were impacted by leaf beetles (Liebert, Huntington, Morton, Sueki, & Acharya, 2016). The METRIC calculations were validated by the eddy flux tower data in their study. That being said, eddy covariance field measurements of ET are prone to large uncertainties and errors when applied to very small, narrow areas like riparian corridors due to advection and flux divergence (Blanken et al., 1997; Steinfeld, Letzel, Raasch, Kanda, & Inagaki, 2006; Wilson et al., 2002). Furthermore, deploying eddy towers is quite expensive and time intensive. Given the similarity between our area of interest and previous field validations of METRIC as well as how resource intensive, non-representative, and uncertain eddy covariance results would be for our specific field site, we chose to utilize METRIC data without additional ground-based validation.

1.3 | Region of interest

This study uses Maggie and Susie Creeks, located in north-eastern Nevada, as case studies for beaver-dam-induced drought buffering (Figure 1). Maggie and Susie Creeks are in a region of Nevada that is classified as an arid climate, according to the Köppen-Geiger Climate

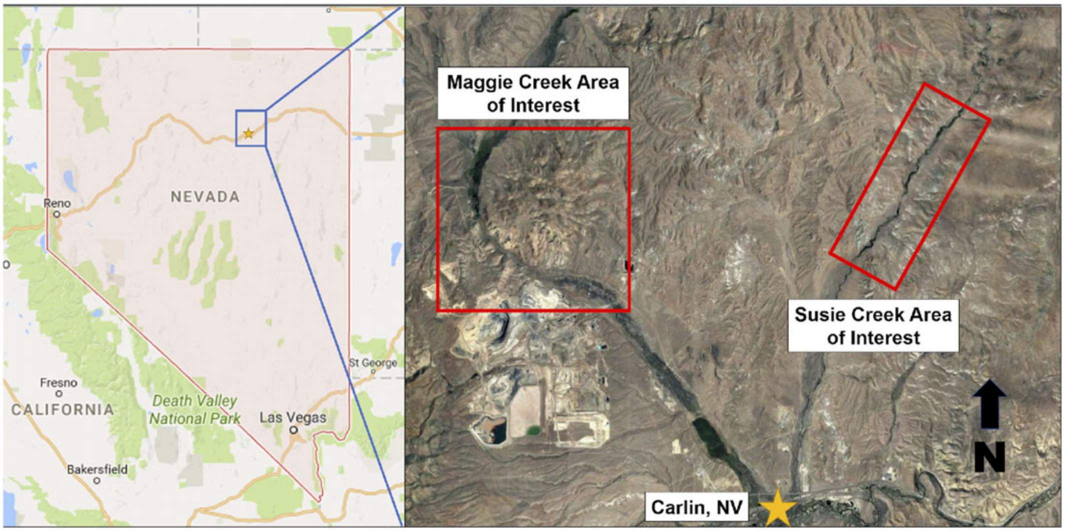

FIGURE 1 Susie and Maggie Creeks, NV. The water in the creeks runs from north to south, ultimately draining into the Humboldt River at the very bottom of the image where the creeks nearly converge in the town of Carlin, NV. Both creeks have significant beaver activity. The areas of interest on Susie and Maggie Creeks are outlined with red boxes. An irrigated alfalfa field is outlined in a blue box, and the remaining landscape is largely sparsely vegetated hillslopes

Classification system (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), and receive 29 cm of precipitation annually (NCEI, 2010). Maggie Creek drains 1,029.2 km^2, and Susie Creek drains 476.7 km^2, both emptying into the Humboldt River. Both creeks run dry or near-dry from approximately late June/early July to October every year according to USGS (2016) streamflow data collected at the lowermost section of each creek.

For much of their recent history, these creeks were significantly incised due to overgrazing by cattle. A restoration effort began in 1993 in which grazing was limited and the creeks were allowed to return to a more natural state. A byproduct of this restoration was the unintentional colonization of the creeks by beaver in the early 2000s. Since 2003, beavers have built hundreds of dams on the creeks. Figure 2 shows transformation of the creek during the restoration process through a series of photographs taken by the Elko Bureau of Land Management (Swanson, Wyman, & Evans, 2015).

The region has sparse vegetation except in the riparian areas and in irrigated alfalfa crops along the lowermost section Maggie Creek (Figure 1). The 2011 Elko Bureau of Land Management Environmental Assessment Report indicated that a recent survey found that the dominant species of riparian vegetation in the area are Coyote willow (*Salix exigua*), common threesquare bulrush (*Scirpus americanus*), baltic rush (*Juncus balticus*), and spikerush (*Eleocharis spp*; BLM, 2011). During periods of drought—including the annual summer dry season—the productivity of hillslope vegetation is limited by water stress. We expect this to result in low ET and NDVI during peak drought months compared with early growing season months when water is more plentiful. The alfalfa crops, however, should maintain high ET and NDVI throughout periods of drought for as long as whoever manages that land continues to irrigate them. Although narrow riparian areas surrounded by arid landscapes can experience advection and have negative sensible heat fluxes and result in ET values higher than even the PET, the alfalfa fields in the study area are also relatively small and located along the stream. Thus, they should experience similar advection. It then follows that the ET of the riparian areas—both with and without beaver—should fall somewhere between the values calculated with METRIC for the streamside alfalfa fields and for the hillslopes.

1.4 | Seasonal and long-term droughts at Susie and Maggie Creeks

Maggie and Susie Creeks experience seasonal droughts every summer, as well as occasional multi-year droughts. The study area has a Mediterranean-type climate, which alternates between hot, dry summers and cold, wet winters. Similar to previous ecohydrology studies, we consider the summer dry season a seasonal drought (Baker et al., 2008; Condit, Engelbrecht, Pino, Perez, & Turner, 2013; Sala & Tenhunen, 1995; Shafroth, Stromberg, & Patten, 2002; Stella & Battles, 2010; Wright, 1991; Wright & Cornejo, 1990). During seasonal droughts, the water demands of vegetation exceed the amount of precipitation for an interval of several months. Under these conditions, vegetation must rely on streamflow, groundwater, and soil moisture to meet its water needs. If these water resources become depleted or are absent altogether, then a common evolutionary response to the drought stress is for the vegetation to undergo senescence and reduce ET (Amlin & Rood, 2002, 2003; Munné-Bosch & Alegre, 2004; Pereira & Chaves, 1995; Rood, Patiño, & Coombs, 2000; Zha et al., 2010). Although senescence is a natural part of the life cycle of vegetation, extended vegetation senescence can have negative impacts on the riparian ecosystem as a whole (Perry, Andersen, Reynolds, Nelson, & Shafroth, 2012; Shafroth et al., 2002; Vivian, Godfree, Colloff, Mayence, & Marshall, 2014). Furthermore, if drought stress persists, then soil moisture can drop below the wilting point of the vegetation and lead to total plant death (Cassel & Nielsen, 1986). Wetlands plants tend to have the majority of their root system located in the top 15–45 cm of the soil

FIGURE 2 A riparian area along Susie Creek from 1991 (pre-restoration) to 2014. Restoration efforts began in 1993, and beavers moved into the creek in the early 2000s. Note the change in water volume, vegetation density, and vegetation greenness in the riparian areas as restoration and beaver colonization took place. Photos from the Elko Bureau of Land Management

and as such can reach the wilting point within a matter of weeks during a drought if no new water is entering the soil (Sipple, 1992).

Seasonal droughts in the study area were identified by comparing the calculated PET of the landscape with the incoming water from precipitation. PET is a measure of the maximum possible total water losses to both plant transpiration and evaporation from the soil and open water surfaces if the system was not water-limited. PET is commonly calculated with the Penman–Monteith equation (Allen et al., 1998) and is calculated this way for this study using values for an alfalfa reference crop. During the summer and early fall (June through August), the PET at Maggie and Susie Creeks is much higher than the incoming precipitation, and thus, we consider it a seasonal drought. It is over these months that the shallow groundwater storage from beaver ponds should have the most pronounced effect on the ET of nearby riparian vegetation. These effects should be noticeable in both normal precipitation years and during multi-year droughts, at least until the ponded volume of water is completely depleted. For this reason, data from all years—both wet and dry—were included in assessing the role of beaver damming in buffering ET during the seasonal droughts that occur predictably each summer.

To identify long-term droughts, we used the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano, Beguería, & López-Moreno, 2010). The SPEI calculates the difference between the current precipitation amounts and the historical long-term averages, subtracts out the PET, and is standardized. The resulting value indicates a water surplus (+) or deficit (−) for the time period considered. The inclusion of PET in the drought index calculations simply helps account for the fact that different areas have different water needs, and those with higher water needs will experience negative effects of decreased precipitation more strongly than those with low water needs. The SPEI for Maggie and Susie Creeks was calculated for each water year (October 1 to September 30) from 1996 to 2016 based on meteorological data collected at the nearby Elko Regional Airport (Figure 3).

It is clear from Figure 3 that the creeks had three distinct multi-year droughts in the last two decades: 2000–2004, 2007–2008, and 2012–2015. We look at the effects that beaver damming has on ET from 2013 to 2016. Including three drought years and one normal precipitation year allows us to quantify the impact of beaver damming on ET during seasonal droughts and assess the extent to which the ET of

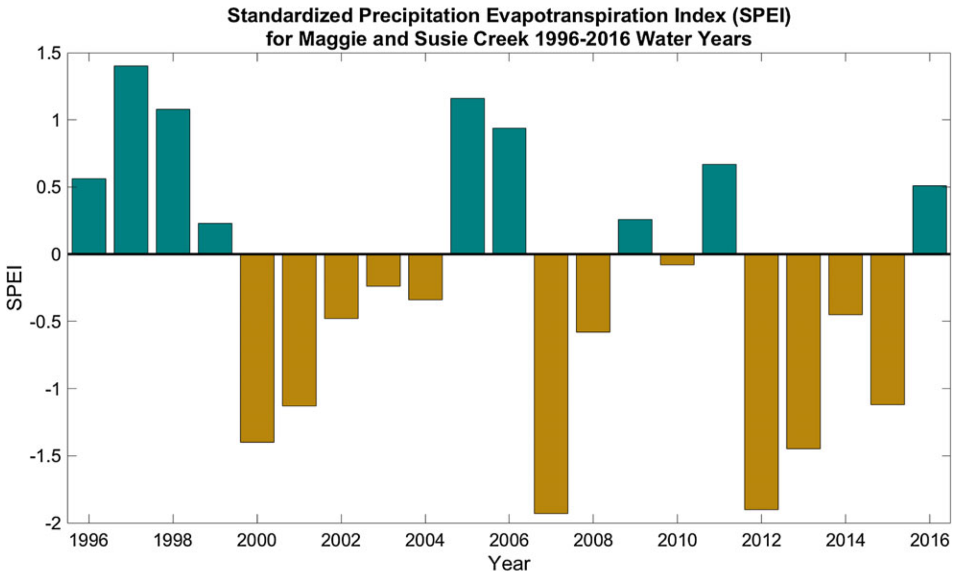

FIGURE 3 Standardized precipitation evapotranspiration index (SPEI) for Maggie and Susie Creeks in Nevada. Negative SPEI values indicate abnormally dry water years and are coloured yellow, whereas positive SPEI values indicate abnormally wet water years and are coloured teal. SPEI less than −1.00 is considered a moderate or greater intensity drought

beaver-dammed riparian areas versus undammed riparian areas is impacted by multi-year droughts.

2 | METHODS

2.1 | Remote sensing with Landsat

This study utilizes Landsat 8 imagery, which is available from April 2013 to the present, has bands with 30 to 100-m resolution, and a 16-day recurrence interval (Anderson, Allen, Morse, & Kustas, 2012; Roy et al., 2014). The Landsat flyover time at Susie and Maggie Creeks is ~11:30 a.m. Pacific Time. Beaver ponds and the nearby riparian areas are relatively small landscape features, so the high resolution of Landsat 8 made it a better choice than other popular ways to measure ET remotely, such as Moderate Resolution Imaging Spectroradiometer, which has much coarser 1-km resolution (Mu, Heinsch, Zhao, & Running, 2007). Additionally, the timing of available of Landsat 8 imagery includes the last three growing seasons (April–October) of the 2012–2015 drought, and one growing season during a non-drought year (2016), which allows us to evaluate the impact that beaver ponds have on ET during both multi-year and seasonal droughts. Only images with <10% cloud cover were included in analysis. A table of the Landsat 8 images used in this study is summarized below (Table 1).

When using the Landsat imagery to make comparisons between dammed and undammed sections of creek, we were careful to exclude any mixed pixels that contained both riparian area and hillslope. Exclusion of pixels was done manually using the Google Earth images (Google, 2018) overlaid with the Landsat pixel outlines. Any pixel containing observable hillslope was removed from analysis. Hillslopes are less vegetated than the riparian areas and not in contact with the stream or ponded water, so any inclusion of pixels containing hillslope would have resulted in underestimation of both ET and NDVI for the riparian area.

TABLE 1 Dates of Landsat images used in the analysis

2013	2014	2015	2016
4/11	4/14	4/17	4/19
5/13	6/1	5/3	6/6
6/30	7/19	6/20	6/22
8/1	8/20	8/23	7/8
8/17	10/7	9/8	7/24
9/18		10/10	8/9
			8/25
			9/10
			9/26

Although we calculated ET and NDVI for each of the dates listed in Table 1, in the interest of being concise, the figures containing maps of ET and NDVI in this paper feature four representative dates: on April 14th and July 19th of the 2014 drought year and on April 19th and July 24th of the 2016 non-drought year. These dates were chosen for two reasons. First, the timing of the two scenes each year is very similar—April 14th and 19th, July 19th and 24th. The similarity in day-of-year allows us to make direct comparisons between the drought and non-drought year without needing to adjust for the timing of the image. Second, looking at both April—before the seasonal drought, and July—the peak of the seasonal drought and also when streamflow is at an annual low point meaning the beaver ponds are the major water source along the creeks (USGS, 2016) enables us to see if the relationship between beaver damming and ET changes as the seasonal summer drought progresses. All figures not containing maps of ET and NDVI utilize the full time series of data.

2.2 | Ground-based meteorological data

The meteorological data collected for use in METRIC are from the Elko Regional Airport, located approximately 30 km east of Susie Creek.

The weather station is at 1,533-m elevation, and the sections of creek studied range from 1,524- to 1,544-m elevation. This weather station has over 100 years of continuous hourly weather observations of almost all the meteorological parameters required by METRIC—temperature, relative humidity, and wind speed. Wind speed was adjusted from the sensor height of 10 m to the 2-m height required by the Penman–Monteith formulation and METRIC using the wind profile power law and a coefficient of 0.143 for neutral stability conditions (Justus & Mikhail, 1976). The only parameter missing is incoming clear sky solar radiation at the time of overpass, $R_{s\downarrow}$ (W), which was modelled based on the latitude of the station as shown in Equation (1) below:

$$R_{s\downarrow} = \frac{G_{sc}\cos\theta_{rel}\tau_{sw}}{d^2}, \tag{1}$$

where G_{sc} is the solar constant (1,376 Wm^{-2}), θ_{rel} is the solar incidence angle in radians, τ_{sw} is the atmospheric transmissivity, and d (m) is the relative Earth–Sun distance (Allen, Tasumi, & Trezza, 2007). The clear sky solar radiation model is an acceptable model for our study because the Landsat images were selected to be at least 90% cloud free and as such are clear sky images. Atmospheric transmissivity, τ_{sw}, was held at a constant value calculated for the elevation of the scene according to Equation (2):

$$\tau_{sw} = \tau_o^{\left(\frac{P}{P_o}\right)}, \tag{2}$$

where τ_o is the clear sky transmissivity at sea level (0.84), P is the pressure at the current elevation, and P_o is the pressure at sea level (Cuffey & Patterson, 2010). Because of the similarity in elevation between the weather station and the creeks studied, no elevation adjustments were made to the meteorological data gathered.

2.3 | Calculations of NDVI and ET

NDVI is calculated from Landsat acquired reflectivity data according to Equation (3) (Tucker, 1979):

$$NDVI = \frac{(\rho_4 - \rho_3)}{(\rho_4 + \rho_3)}, \tag{3}$$

where ρ_4 is the near-infrared band reflectivity (Landsat 8 band 4) and ρ_3 is the red band reflectivity (Landsat 8 band 3). The Landsat images used were USGS Level 2 Surface Reflectance images and have already had atmospheric corrections applied. All images came with a quality assessment statement regarding whether the integrity of data had been affected by instrument artefacts or atmospheric conditions. None of the images used in this study had any quality issues. We use NDVI to assess vegetation health on both seasonal and multi-year drought timescales, and NDVI is thus a measure of drought buffering.

ET is calculated as the residual of a surface energy balance. For each pixel in a Landsat 8 scene, METRIC calculates the latent energy (LE) according to Equation (4) below (Allen, Tasumi, & Trezza, 2007):

$$LE = R_n - G - H. \tag{4}$$

Latent energy (LE), net radiation at the surface (R_n), the ground heat flux (G), and the sensible heat flux (H) are calculated as Wm^{-2}. METRIC uses the narrow-band reflectance and surface temperature collected by the Landsat 8 satellite to calculate R_n, estimates G from R_n and the vegetation indices—including NDVI, and estimates H from surface temperatures, surface roughness, and wind speed. METRIC is internally calibrated by anchor pixels selected at hot and cold points in the scene. Hot pixels correspond to low ET areas—such as bare, dry dirt; cold pixels correspond to high ET areas—such as irrigated alfalfa. The hot and cold pixels were chosen using the CITRA-MCB automated process (Olmedo, Ortega-Farías, & de la Fuente-Sáiz, 2015). In the CITRA-MCB process, the code walks through all the pixels in the scene and finds a user-defined number of the hottest and coldest pixels. To find hot pixels, it looks for pixels that both maximize surface temperature and minimize leaf area index. To find cold pixels, it looks for pixels that minimize surface temperature and maximize leaf area index. To ensure that the automated pixel selection made sense, pixel locations were overlaid on a Google Earth satellite image (Google, 2018) and checked that they corresponded to bare soil (hot pixels) and lush, green vegetation (cold pixels).

The instantaneous ET (ET_{inst}, mm hr^{-1}) at the time of Landsat overpass is calculated by dividing the latent energy at each pixel by the density of water, ρ_w, and the latent heat of vaporization of water, λ, then multiplied by 3,600 to convert from seconds to hours:

$$ET_{inst} = 3,600\frac{LE}{\rho_w\lambda}. \tag{5}$$

It is then divided by the Penman–Monteith modelled instantaneous ET (mm hr^{-1}) for a 0.5-m-tall alfalfa reference crop (ET_r) given the same meteorological parameters (Allen et al., 1998). In our study, these meteorological parameters were the ones gathered from the Elko Regional Airport MET station. The resulting value is the fractional ET, ET_rF, as shown in Equation (6).

$$ET_rF = \frac{ET_{inst}}{ET_r}. \tag{6}$$

It is assumed that instantaneous ET_rF computed at the image time is the same as the average ET_rF over the 24-hr period (Allen, Tasumi, & Trezza, 2007). From the fractional ET, METRIC calculates the daily ET by multiplying the fractional ET by the 24-hr cumulative reference ET for the 0.5-m alfalfa crop (ET_{r_24}; mm day^{-1}) and a correction factor for sloping terrain, C_{rad}, calculated from an input digital elevation model.

$$ET_{24} = C_{rad}(ET_rF)(ET_{r\_24}). \tag{7}$$

Although METRIC has been shown to have a larger error on steep slopes (~30%)—such as some of those nearby to Maggie Creek—the error is small on low slopes and flat lands (<5%; Allen, Trezza, Kilic, Tasumi, & Li, 2013). The actual riparian areas we studied are located on low and flat slopes, so the error in our calculations for these areas is expected to be small. It is possible that there is some unaccounted-for advection in the ET results, but this advection and the resultant negative sensible heat flux would be expected to occur throughout the riparian zone as well as in the streamside alfalfa. It is also expected to be small in value. The hillslope ET calculations should not have any advection bias. The calculations of daily ET are used to in our analysis to assess water access and use by riparian vegetation on both seasonal and multi-year drought timescales and is thus a measure of drought buffering.

2.4 | Classification of dammed and undammed riparian areas

To assess the extent of beaver activity, beaver dams along both creeks were identified, measured, and categorized as active or inactive based on satellite images acquired through Google Earth (Google, 2014). Dammed versus undammed riparian areas on Maggie and Susie Creeks were identified visually using the Google Earth imagery. The width of the riparian areas was determined based on transitions between riparian vegetation species and grasses found on the drier hillslopes and changes in elevation greater than 2 m from the stream. For both creeks, only riparian areas with similar average widths were compared against one another.

The spacing and density of dams along Susie Creek is variable. There are no large sections that are distinctly dammed or undammed. We utilized this variability in damming to investigate the degree of correlation between increasing beaver activity and increased ET. In order to quantify the variable beaver damming on Susie Creek, we defined damming intensity as the total length of dams within a 500-m length of creek. The total length of the stream in the area of interest (Figure 1) was broken into 500-m blocks, and the total length of beaver dams within each block was measured. The downstream point of the creek in the area of interest is the start of Block 1, and Block 25 ends at the most upstream point of the creek (12.5 km upstream).

Maggie Creek, on the other hand, is essentially broken into two large sections: a heavily dammed riparian area and a completely undammed riparian area. The stark contrast in beaver activity in the riparian areas on Maggie Creek allowed us to assess the role beaver damming plays in elevating and maintaining the riparian ET by comparing the two sections against one another without needing to control for varying intensity of damming.

3 | RESULTS

3.1 | Intensity of damming versus ET on Susie Creek

Along the stretch of Susie Creek examined, the ET signal from the riparian area is non-uniformly elevated (Figure 4).

The portions of creek with most intensely elevated ET visually correspond to the portions of creek with the most intense beaver damming, whereas areas with lower ET correspond to stretches of creek with relatively little beaver damming. Small day-to-day variations in ET are expected—air temperature, humidity, and wind speed all vary slightly on a daily basis within a given month. These day-to-day variations are much smaller than monthly or seasonal variations in ET. The contrast between the beaver dammed sections of Susie Creek and the rest of the landscape is greatest in the July images, but the correlation between damming and elevated ET appears to be present to some extent in all four images. Extracting the average ET in each 500-m section of creek and plotting it against the damming intensity shows this correlation more quantitatively (Figure 5).

The data show a positive correlation between increased damming and elevated ET going from no damming (0-m dam length per block) up to low/moderate damming (~150-m dam length per block). Additional damming beyond ~150 m/block seems to have little additional effect, if any, on the ET. Instead, the ET values level off and have more variability as damming intensity continues to increase. We fit a linear model (blue lines) to the data up to 150 m/block damming intensity for all dates examined, although only four representative dates are shown in Figure 5. The average correlation coefficient between damming intensity and ET up to 150 m/block was 0.56. Overall, the results from the Susie Creek damming intensity analysis indicate that increased beaver damming is associated with increased ET but that the relationship is not perfectly linear and there is possibly a threshold where the effects of beaver damming and water availability on ET are no longer the main limiting factor in ET.

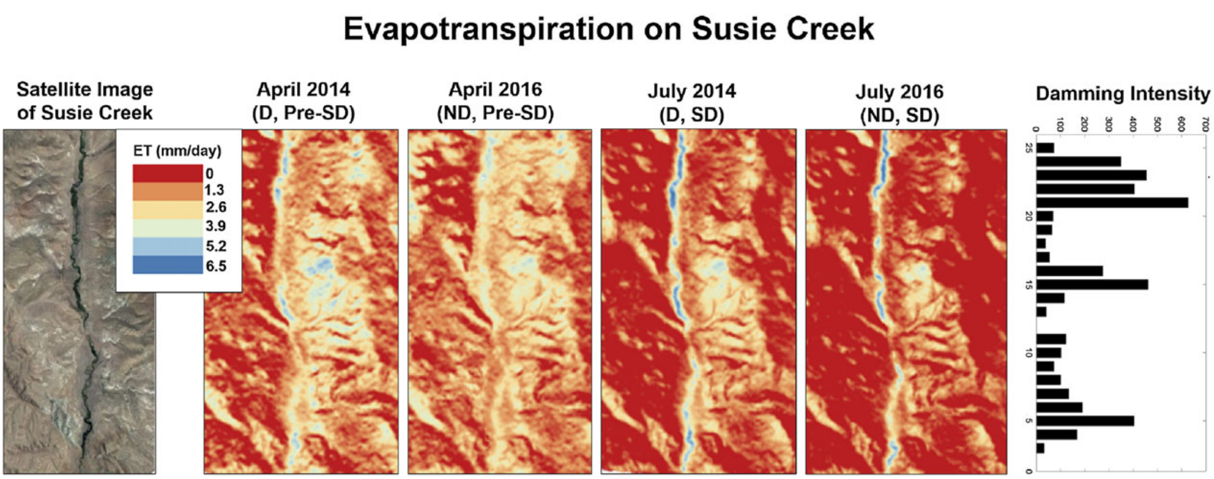

FIGURE 4 Evapotranspiration (ET) data from Susie Creek for April 2014, April 2016, July 2014, and July 2016. "D" signifies it was a drought year, "ND" signifies a non-drought year, "Pre-SD" is pre-seasonal drought, and "SD" is seasonal drought. Note that in all months, it visually appears that there are ET hotspots near where there is the most intense beaver damming

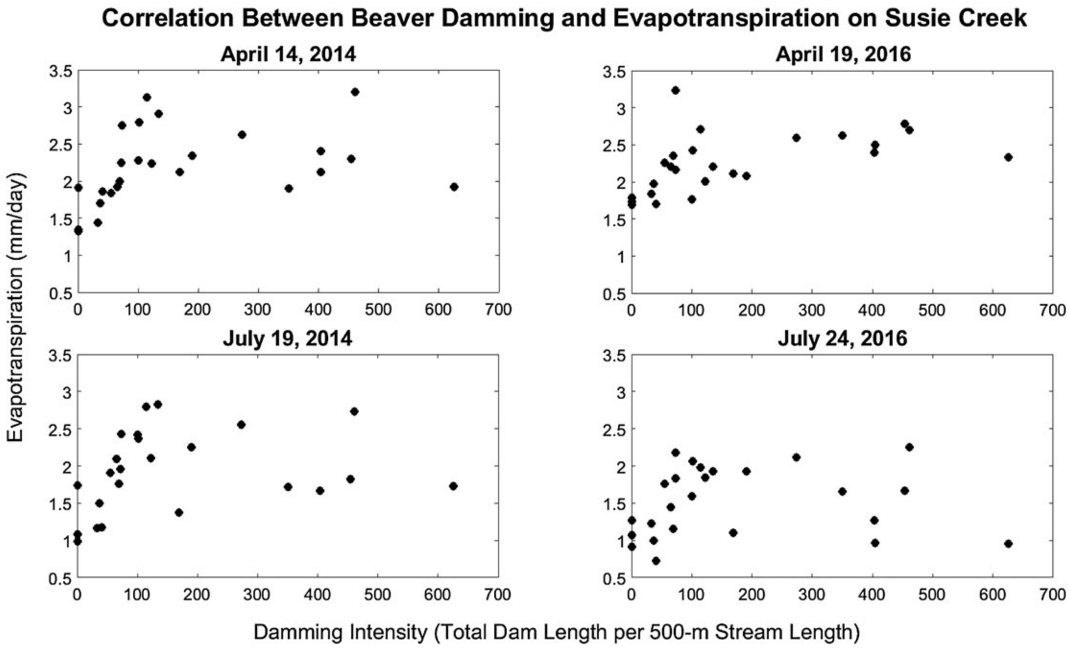

FIGURE 5 Evapotranspiration as a function of damming intensity. Going from no damming (0-m dam length/block) to light/moderate damming (~150-dam length/block), there again appears to be a positive correlation between the two variables. However, beyond ~150-m-total dam length, the evapotranspiration signal stops increasing and has more variability. Linear models were fit to the data with <150 total dam length per block, and they are shown as blue lines

3.2 | ET and NDVI of dammed and undammed riparian areas on Maggie Creek

Unlike Susie Creek's varying intensity of damming, Maggie Creek is heavily dammed on its upper stretch (>150-m dam length per 500-m steam length) and has no damming at all on the lower stretch. This makes comparing dammed and undammed riparian areas straightforward and eliminates the need to control for extent of damming. The two creeks are otherwise similar in terms of vegetation type, topography, and riparian area width. Our results from Susie Creek suggest that any differences in the ET between the upper and lower sections of Maggie Creek are most likely associated with the difference in beaver activity between them.

The ET images show a stark difference between the dammed and undammed portions of Maggie Creek (Figure 6, left). ET is clearly elevated where the creek has been dammed by beavers and that signal is more prominent during the summer. Although the ET values on the slopes immediately adjacent to the Maggie Creek riparian areas are likely calculated as too high due to the sensitivity of METRIC to steep slopes, the riparian areas are located on low slopes (<5%) and as such have relatively low errors. In the drought year (2014), the undammed riparian area has very low ET and looks more similar to the

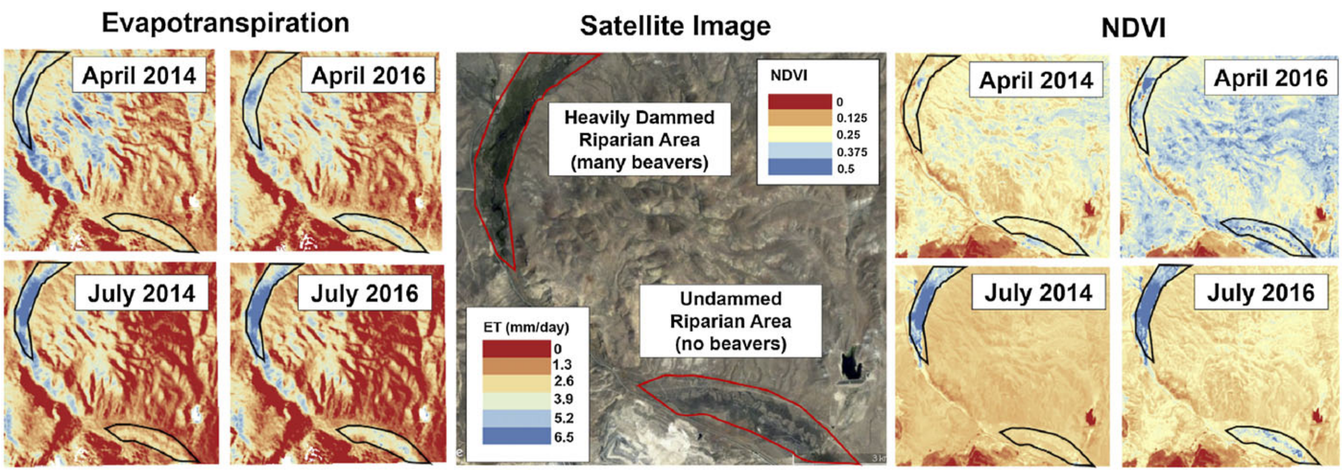

FIGURE 6 Centre: A satellite image of the area of interest on Maggie Creek with the dammed and undammed riparian areas outlined in red. Left: Raw evapotranspiration (ET) images of Maggie Creek during the spring (April) and summer (July) of both a drought year (2014) and a normal precipitation year (2016). Note that in all years, the beaver-dammed area has a higher ET than the undammed area and that difference peaks in the summer and during the drought. Right: Same for normalized difference vegetation index (NDVI)

surrounding landscape than the riparian area with beavers. In the wet year (2016), the undammed riparian area is still lower ET than the dammed riparian area, but there is a streak of high ET through the middle nearest to the creek, which resembles the ET of the dammed riparian area. This suggests that given more precipitation, the difference in ET between undammed riparian areas and dammed riparian areas may be smaller.

The riparian area with beavers is heavily dammed and may have more standing water, which could produce a high ET signal just from evaporation off the water surface. To determine whether the higher ET signals in the beaver-dammed riparian area were primarily from increased plant transpiration or increased water evaporation, NDVI was calculated (Figure 6, right). The differences between dammed and undammed riparian areas are even more stark in the NDVI results than in the ET results, implying that the differences are more likely due to plant transpiration. To quantitatively test whether the increased ET in the riparian areas was due to increased vegetation transpiration or to increased open water/soil evaporation, we plotted NDVI against ET for both the beaver-dammed riparian area and the undammed riparian area (Figure 7). In the data analysis, pixels with a negative NDVI value were assumed to be open water and were excluded.

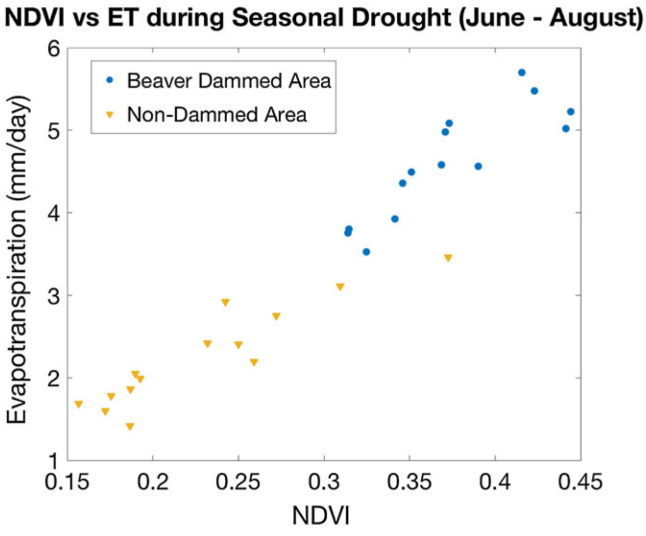

FIGURE 7 Normalized difference vegetation index (NDVI) versus evapotranspiration (ET) for both dammed and undammed riparian areas. The positive linear relationship indicates that the increased ET signal observed is coming from healthier or more dense vegetation transpiration, not open water or soil evaporation

If the ET increase had been from mostly evaporation, NDVI would have remained constant and ET increased. The positive linear relationship observed between NDVI and ET in Figure 7 confirms that the elevated ET signals coming from the beaver areas are very likely due to more dense and healthier vegetation transpiration as opposed to open water or soil evaporation.

3.3 | ET and NDVI in the context of the landscape

We compared the ET from riparian areas that have been dammed by beavers to the ET of several other vegetated elements of the landscape—the undammed riparian areas, an irrigated alfalfa field, and the vegetation on hillslopes—over the 2013–2016 period (Figure 8). The Penman–Monteith PET is shown as well for comparison.

Figure 8 shows that beaver-dammed riparian area and irrigated alfalfa are most similar in shape and magnitude of ET through time, whereas the undammed riparian area appears more similar to the hillslope vegetation. Beaver-dammed areas and alfalfa have a seasonal arc in ET, peaking in June/July, then decreasing into the fall. The alfalfa ET calculated with METRIC never quite reaches the PET despite the fact that our PET was calculated for an alfalfa reference crop. We attribute this to imperfect irrigation practices and crop spacing producing slightly lower ET than predicted. It is also possible that because the Landsat thermal pixels are 100 m × 100 m, there are still some edge effects impacting the results even after the manual mixed pixel exclusion process. We expect these errors to be small and not impact the overall trend of the data. Areas without beaver damming and hillslopes had a tendency to just decrease throughout the growing season—likely due to increasing water stress. The NDVI calculations over the same time period show similar results (Figure 9).

In Figure 9, the NDVI of each landscape element has a similar shape to the respective ET in Figure 8. This again confirms that observed differences in ET between the four landscape elements (dammed riparian areas, undammed riparian areas, irrigated alfalfa, and hillslopes) are largely due to differences in vegetation transpiration as opposed to soil or open water evaporation. Additionally, it

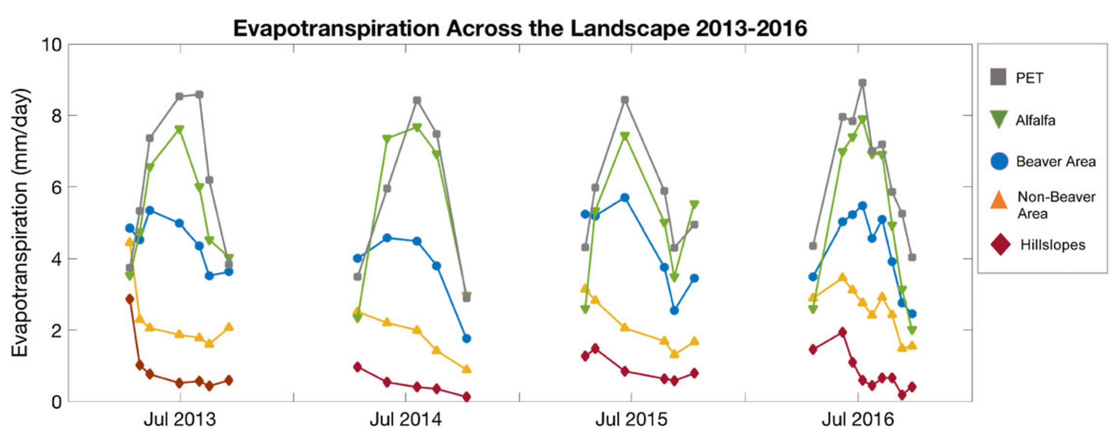

FIGURE 8 Evapotranspiration of beaver-dammed riparian areas put in the context of other landscape elements: undammed riparian areas, irrigated alfalfa, and hillslopes disconnected from the streams. Potential evapotranspiration (PET) is shown for comparison as well

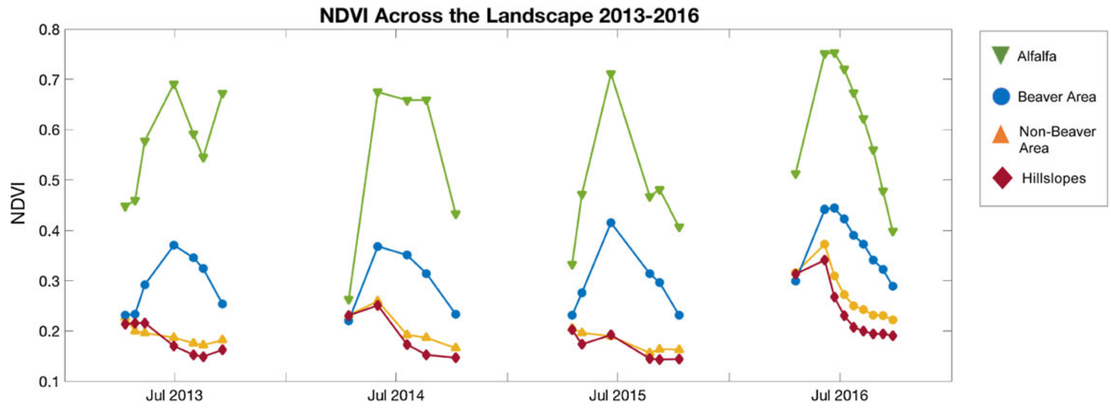

FIGURE 9 Normalized difference vegetation index (NDVI) of beaver-dammed riparian areas put in the context of other landscape elements: undammed riparian areas, irrigated alfalfa, and hillslopes disconnected from the streams

shows that beaver-dammed riparian areas are more similar in vegetation health and/or density to the irrigated alfalfa than to either the non-beaver riparian areas or the hillslopes.

3.4 | Drought analysis

3.4.1 | Seasonal drought

The data from 2013 to 2016 showed that both measures of drought buffering (ET and NDVI) were consistently higher in the riparian areas with beavers than in those without beavers (Figure 10).

We found that the ET of riparian areas with beaver damming was 50–150% higher than the ET in riparian areas without beaver damming and that NDVI in dammed riparian areas was 6–88% higher than in undammed areas. The difference between the dammed and undammed areas peaks in the summer—the time when water needs are highest and water availability is lowest. Figure 10 also shows that for both ET and NDVI, the greatest difference between the two areas is June–August—the seasonal drought. This suggests that on Maggie Creek, beaver-dammed riparian areas are better buffered against seasonal droughts than riparian areas that do not have beaver damming.

3.4.2 | Multi-year drought

Although the beaver-dammed riparian areas clearly maintain vegetation health better than the riparian areas during seasonal droughts, the question remains as to whether the drought buffering was more pronounced during the drought years (2013–2015) than the non-drought year (2016). Figure 11 shows the data from each year plotted on top one another to allow for direct comparisons between drought and non-drought years for the beaver dammed and undammed riparian areas.

For the beaver-dammed riparian area (blue, Figure 11), the drought (dashed line) and non-drought (solid line) data do not have distinctly different shapes or magnitudes. There are two takeaways from this: first, this shows that the drought buffering capacity of the beaver-dammed riparian area did not diminish significantly over during the studied multi-year drought. Second, vegetation in the beaver-dammed riparian area did not fare any worse during the multi-year drought that it did during the normal precipitation year. This indicates that the extent of beaver damming on Maggie Creek was enough to fully buffer the effects of the multi-year drought on the riparian vegetation.

For the riparian area without beaver damming (yellow, Figure 11), the drought (dashed line) and non-drought (solid line) data have different shapes and different magnitudes. All the data from the drought years essentially just decrease from a high value in April—likely due to the vegetation undergoing senescence at the beginning of the summer and staying senesced throughout. The shapes of the drought year data have no arc and do not look similar to the beaver-dammed area's drought data. During the non-drought year, however, the shape of the ET for the riparian area without beaver damming was similar to the riparian area with beaver damming, and no longer had the monotonously decreasing shape like it did during the drought years.

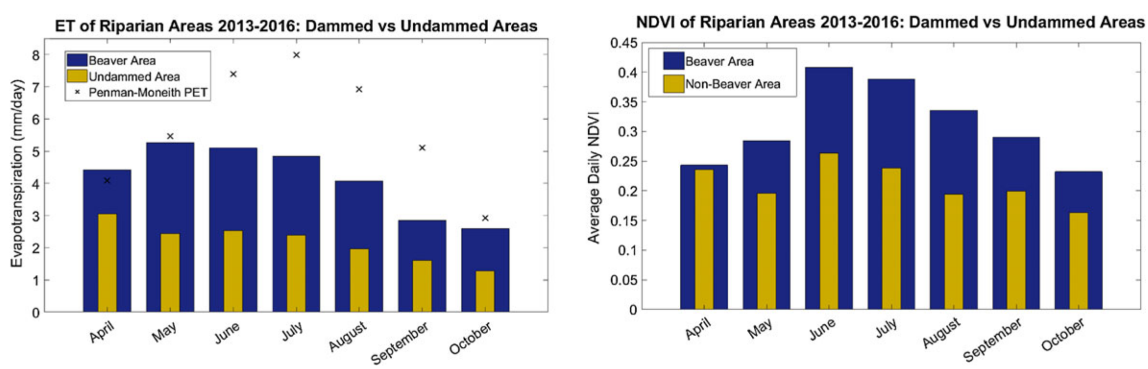

FIGURE 10 Left: The evapotranspiration (ET) of riparian areas with beaver versus riparian areas without beaver. Right: The normalized difference vegetation index (NDVI) of dammed and undammed riparian areas. PET: potential evapotranspiration

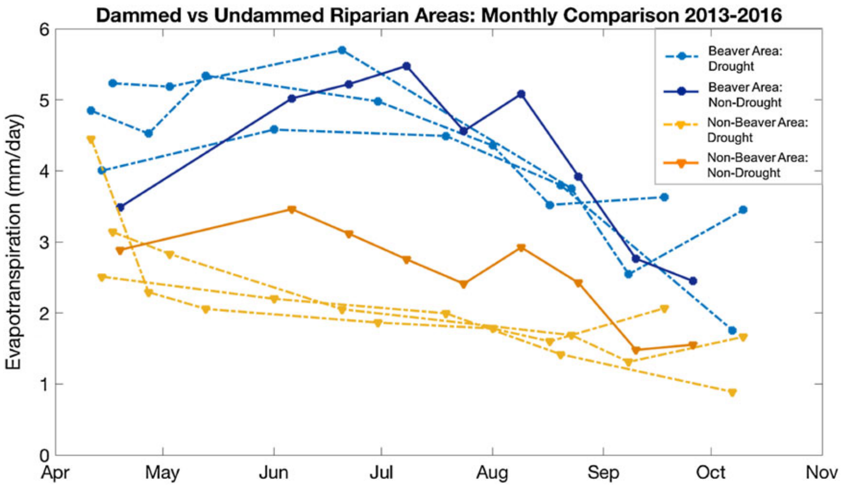

FIGURE 11 Evapotranspiration of riparian areas with and without beaver. Each year from 2013 to 2016 is individually plotted and colour coded by beaver versus no-beavers (blues vs. yellow) and drought versus non-drought (light dotted line vs. dark solid line)

Vegetation in the undammed area likely still underwent senescence, but it appears to be for a shorter duration and begin later in the summer than it did during the drought years. Additionally, it was higher in magnitude than the three drought years. This suggests that the riparian area without beaver damming was sensitive to multi-year droughts.

In summary, these results showed that beaver-dammed riparian areas had largely the same ET signal for drought years and the non-drought year, implying that they are well-buffered against extended periods of drought. Riparian areas without beaver, however, appear to have been affected by the multi-year drought and appeared to begin senescing very early in the summer, implying that they are not as well-buffered against extended periods of drought.

4 | DISCUSSION AND CONCLUSIONS

We proposed that beaver-dam-induced drought buffering occurs via water seepage from the beaver ponds into the nearby soil, where it is accessible to the roots of riparian vegetation. Our data showed that within the context of the landscape, the beaver-dammed riparian areas have ET and NDVI signals more similar to irrigated crops than to either undammed riparian areas or hillslope vegetation. This similarity supports the idea that the drought buffering mechanism associated with beaver damming works like an underground irrigation system for the riparian vegetation, in which water seeps from the beaver ponds into the shallow subsurface.

We demonstrated that increased beaver damming is associated with elevated ET signals using the data from Susie Creek. We found a linear positive relationship between damming intensity and ET going from no beaver damming to ~150-m dam length per 500-m stream segment. However, beyond 150-m dam length/500-m stream segment, the effects of increased damming failed to produce increasingly higher ET values. This suggests that there is a threshold beyond which some other factor limits ET more than the availability of ponded water. We suspect that this threshold may be associated with physical characteristics of the riparian area—such as soil drying rate, soil porosity, shape of the hyporheic zone, and maximum vegetation density.

We hypothesized that the drought buffering mechanism associated with beaver damming is at least sustainable on seasonal timescales, where the beaver ponds are refilling each winter/spring with precipitation and slowly releasing it through hot, dry summers. This hypothesis was confirmed by our results, which showed that beaver-dammed riparian areas have consistently higher ET during seasonal droughts than undammed areas. Our NDVI calculations indicated that the increase in ET was more likely due to increased plant productivity and/or density rather than more open water or soil evaporation. Furthermore, we predicted that as long as there was water remaining in the beaver ponds, the drought buffering would be able to persist through multi-year droughts. Our results did not show a significant decrease in the ET of the beaver-dammed area as the multi-year drought progressed. The riparian area without beaver damming, on the other hand, was negatively impacted by the multi-year drought and showed a regain of vegetation health once the drought ended. This supports the idea that drought buffering associated with beaver damming can be effective on multi-year timescales in additional to seasonal ones.

A major limitation of this study is that it is a site-specific case study, and although we suspect the results may be more generalizable, we do not currently have data to support that claim. Additionally, because of the transient nature of beaver damming (beaver dams come in and out of repair and beavers move up and down stream looking for fresh food; Neff, 1957; Ruedemann & Schoonmaker, 1938; Woo & Waddington, 1990) and lack of a detailed long-term record of dam locations and sizes along the creeks, we were only able to justify using the 4 years of Landsat data centred around a data set of known beaver dam distribution data. Although we chose a field site where we expected differences in topography, geology, and soil hydraulic parameters to be minimized, it is likely that the undammed riparian areas are not completely analogous to the beaver-dammed riparian areas. For example, it is known that beaver ponds accumulate sediment—particularly fine sediments and organic matter—and can transform streams into true wetlands and wet meadows. We did not attempt to separate out the effects that changes in soil properties, connection to floodplain, vegetation type changes would have caused—they were all considered beaver-related effects and discussed as an innate difference between dammed and undammed riparian areas.

Despite the limitations of this study, we have shown that these particular beaver-dammed riparian areas are better equipped to thrive during droughts than riparian areas without beavers. Our results are not easily explained by any process that would be site-specific and only applicable at Maggie and Susie Creeks—such as a beetle kill and high variation in soil type or plant species along the creeks. We expect that further research will show similar results in arid watersheds across North America.

All of the arid and semi-arid states in the western USA have lost a huge percentage of wetland habitat since the 1700s—with California having lost 91%, Nevada 52%, Idaho 56%, and Colorado 50% (Mitsch & Gosselink, 1993). These same states also have extensive habitat that could be colonized by beaver in the coming decades (Macfarlane et al., 2015), potentially restoring some of the lost wetland habitat in a way that is more resilient to future stressors like drought. Our study showed that beaver-dammed riparian areas may be better buffered against droughts than riparian areas without beaver, and so we encourage land managers to consider encouraging beaver dam building activity in future management plans for arid and semi-arid landscapes. Further modelling, remote sensing, and field work is necessary to fully characterize the role that beavers will play in the future of wetland habitat creation and maintenance in arid and semi-arid climates, but we believe our study shows the potential for their impacts to be important and worth consideration.

ACKNOWLEDGEMENTS

This research was conducted with Government support under and awarded by DoD, Air Force Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG) Fellowship, 32 CFR 168a. Emily Fairfax also received support from, the Birkeland Graduate Scholarship, and a Geological Society of America Graduate Research Grant. Thank you to an anonymous reviewer for providing us with detailed comments, which greatly increased the quality and clarity of this manuscript.

ORCID

Emily Fairfax http://orcid.org/0000-0001-8480-1777
Eric E. Small http://orcid.org/0000-0002-5010-4954

REFERENCES

Allen, R., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration—Guidelines for computing crop water requirements—Paper 56. *FAO Irrigation and Drainage*, 1–15.

Allen, R. G., Tasumi, M., Morse, A., & Trezza, R. (2005). A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. *Irrigation and Drainage Systems*, *19*, 251–268.

Allen, R. G., Tasumi, M., Morse, A., Trezza, R., Wright, J. L., Bastiaanssen, W., … Robison, C. W. (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Applications. *Journal of Irrigation and Drainage Engineering*, *133*(4), 395–406. https://doi.org/10.1061/(asce)0733-9437(2007)133:4(395)

Allen, R. G., Tasumi, M., & Trezza, R. (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. *Journal of Irrigation and Drainage Engineering*, *133*(4), 380–394. https://doi.org/10.1061/(asce)0733-9437(2007)133:4(380)

Allen, R. G., Trezza, R., Kilic, A., Tasumi, M., & Li, H. (2013). Sensitivity of Landsat-scale energy balance to aerodynamic variability in mountains and complex terrain. *JAWRA Journal of the American Water Resources Association*, *49*(3), 592–604. https://doi.org/10.1111/jawr.12055

Amlin, N. M., & Rood, S. B. (2002). Comparative tolerances of riparian willows and cottonwoods to water-table decline. *Wetlands*, *22*(2), 338–346. https://doi.org/10.1672/0277-5212(2002)022[0338:Ctorwa]2.0.Co;2

Amlin, N. M., & Rood, S. B. (2003). Drought stress and recovery of riparian cottonwoods due to water table alteration along Willow Creek, Alberta. *Trees*, *17*, 351–358. https://doi.org/10.1007/s00468-003-0245-3

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

Anderson, M. C., Allen, R. G., Morse, A., & Kustas, W. P. (2012). Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. *Remote Sensing of Environment*, *122*, 50–65. https://doi.org/10.1016/j.rse.2011.08.025

Baker, I. T., Prihodko, L., Denning, A. S., Goulden, M., Miller, S., & da Rocha, H. R. (2008). Seasonal drought stress in the Amazon: Reconciling models and observations. *Journal of Geophysical Research: Biogeosciences*, *113*(G1), n/a–n/a. https://doi.org/10.1029/2007jg000644

Blanken, P. D., Black, T. A., Yang, P. C., Neumann, H. H., Nesic, Z., Staebler, R., … Lee, X. (1997). Energy balance and canopy conductance of a boreal aspen forest: Partitioning overstory and understory components. *Journal of Geophysical Research: Atmospheres*, *102*(D24), 28915–28927. https://doi.org/10.1029/97jd00193

BLM. (2011). *Maggie and Susie Creek Fish Barriers Environmental Assessment*.

Briggs, M. A., Lautz, L. K., Hare, D. K., & González-Pinzón, R. (2013). Relating hyporheic fluxes, residence times, and redox-sensitive biogeochemical processes upstream of beaver dams. *Freshwater Science*, *32*(2), 622–641. https://doi.org/10.1899/12-110.1

Burns, D. A., & McDonnell, J. J. (1998). Effects of a beaver pond on runoff proceses: Comparison of two headwater catchments. *Journal of Hydrology*, *205*, 248–264.

Butler, D. R., & Malanson, G. P. (2005). The geomorphic influences of beaver dams and failures of beaver dams. *Geomorphology*, *71*(1–2), 48–60. https://doi.org/10.1016/j.geomorph.2004.08.016

Carillo, C., Bergman, D., Taylor, J., Nolte, D., & Viehoever, P. (2009). An overview of historical beaver management in Arizona. *Proceedings of the 13th WDM Conference, USDA National Wildlife Research Center - Staff Publications* (Paper 882), 216–224.

Carlson, T. N., & Ripley, D. A. (1997). On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment*, *62*, 241–252.

Cassel, D. K., & Nielsen, D. R. (1986). Field capacity and available water capacity. In *Methods of soil analysis: Part 1—Physical and mineralogical methods (methodsofsoilan1)* (pp. 901–926). %@ 0891188649

Condit, R., Engelbrecht, B. M., Pino, D., Perez, R., & Turner, B. L. (2013). Species distributions in response to individual soil nutrients and seasonal drought across a community of tropical trees. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(13), 5064–5068. https://doi.org/10.1073/pnas.1218042110

Cuffey, K. M., & Patterson, W. S. B. (2010). *The physics of glaciers* (4th ed.). United States of America: Elsevier.

Fisher, J. B., Whittaker, R. J., & Malhi, Y. (2011). ET come home: Potential evapotranspiration in geographical ecology. *Global Ecology and Biogeography*, *20*(1), 1–18. https://doi.org/10.1111/j.1466-8238.2010.00578.x

French, A. N., Hunsaker, D. J., & Thorp, K. R. (2015). Remote sensing of evapotranspiration over cotton using the TSEB and METRIC energy balance models. *Remote Sensing of Environment*, *158*, 281–294. https://doi.org/10.1016/j.rse.2014.11.003

Gibson, P. P., & Olden, J. D. (2014). Ecology, management, and conservation implications of North American beaver (Castor canadensis) in dryland streams. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24*(3), 391–409. https://doi.org/10.1002/aqc.2432

Gibson, P. P., Olden, J. D., & O'Neill, M. W. (2015). Beaver dams shift desert fish assemblages toward dominance by non-native species (Verde River, Arizona, USA). *Ecology of Freshwater Fish*, *24*(3), 355–372. https://doi.org/10.1111/eff.12150

Google. (2014). Nevada satellite imagery. From Google Earth

Google. (2018). Nevada satellite imagery: Susie and Maggie Creek Area. From Google Earth

Green, K. C., & Westbrook, C. J. (2009). Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *BC Journal of Ecosystems and Management*, *10*(1), 68–79.

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

Hammerson, G. A. (1994). Beaver (*Castor canadensis*): Ecosystem alterations, management, and monitoring. *Natural areas journal*, *14*(1), 44–57.

Hawkins, B. A., Field, R., Cornell, H. V., Currie, D. J., Guégan, J.-F., Kaufman, D. M., … Turner, J. R. G. (2003). Energy, water, and broad-scale geographic patterns of species richness. *Ecology*, *84*(12), 3105–3117.

Hillman, G. R. (1998). Flood wave attenuation by a wetland following a beaver dam failure on a second order boreal stream. *Wetlands*, *18*(1), 21–34.

Huntington, J., McGwire, K., Morton, C., Snyder, K., Peterson, S., Erickson, T., … Allen, R. (2016). Assessing the role of climate and resource management on groundwater dependent ecosystem changes in arid environments within the Landsat archive. *Remote Sensing of Environment*, *185*, 186–197. https://doi.org/10.1016/j.rse.2016.07.004

Janzen, K., & Westbrook, C. J. (2011). Hyporheic flows along a channelled peatland: Influence of beaver dams. *Canadian Water Resources Journal*, *36*(4), 331–347. https://doi.org/10.4296/cwrj3604846

Jin, L., Siegel, D. I., Lautz, L. K., & Otz, M. H. (2009). Transient storage and downstream solute transport in nested stream reaches affected by beaver dams. *Hydrological Processes*, *23*(17), 2438–2449. https://doi.org/10.1002/hyp.7359

Justus, C. G., & Mikhail, A. (1976). Height variation of wind speed and wind distributions statistics. *Geophysical Research Letters*, *3*(5), 261–264.

Karran, D. J., Westbrook, C. J., Wheaton, J. M., Johnston, C. A., & Bedard-Haughn, A. (2016). Rapid surface water volume estimations in beaver ponds. *Hydrology and Earth System Sciences Discussions.*, 1–26. https://doi.org/10.5194/hess-2016-352

Kauffman, J. B., Beschta, R. L., Otting, N., & Lytjen, D. (1997). An ecological perspective of riparian and stream restoration in the western United States. *Fisheries*, *22*(5), 12–24. https://doi.org/10.1577/1548-8446(1997)022<0012:aepora>2.0.co; 2

Knopf, F. L., Johnson, R. R., Rich, T., Samson, F. B., & Szaro, R. C. (1988). Conservation of riparian ecosystems in the United States. *The Wilson Bulletin*, *100*(2), 272–284.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Laio, F., Porporato, A., Fernadnez-Illescas, C. P., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress IV. Discussion of real cases. *Advances in Water Resources*, *24*, 745–762.

Lautz, L. K., Siegel, D. I., & Bauer, R. L. (2006). Impact of debris dams on hyporheic interaction along a semi-arid stream. *Hydrological Processes*, *20*(1), 183–196. https://doi.org/10.1002/hyp.5910

Levine, R., & Meyer, G. A. (2014). Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA. *Geomorphology*, *205*, 51–64. https://doi.org/10.1016/j.geomorph.2013.04.035

Liebert, R., Huntington, J., Morton, C., Sueki, S., & Acharya, K. (2016). Reduced evapotranspiration from leaf beetle induce tamarisk defoliation in the Lower Virgin River using satellite-based energy balance. *Ecohydrology*, *9*, 179–193. https://doi.org/10.1002/eco.1623

Lowry, M. M. (1993). Groundwater elevations and temperature adjacent to a beaver pond in central Oregon. Oregon State University Dept of Forest Engineering, Thesis.

Macfarlane, W. W., Gilbert, J. T., Jensen, M. L., Gilbert, J. D., Hough-Snee, N., McHugh, P. A., … Bennett, S. N. (2016). Riparian vegetation as an indicator of riparian condition: Detecting departures from historic condition across the North American West. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2016.10.054

Macfarlane, W. W., Wheaton, J. M., Bouwes, N., Jensen, M. L., Gilbert, J. T., Hough-Snee, N., & Shivik, J. A. (2015). Modeling the capacity of riverscapes to support beaver dams. *Geomorphology*. https://doi.org/10.1016/j.geomorph.2015.11.019

Mitsch, W. J., & Gosselink, J. G. (1993). *Wetlands* (2nd ed.). New York: John Wiley.

Mu, Q., Heinsch, F. A., Zhao, M., & Running, S. W. (2007). Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sensing of Environment*, *111*(4), 519–536. https://doi.org/10.1016/j.rse.2007.04.015

Munné-Bosch, S., & Alegre, L. (2004). Die and let live: Leaf senescence contributes to plant survival under drought stress. *Functional Plant Biology*, *31*, 203–216.

Naiman, R. J., Melillo, J. M., & Hobbie, J. E. (1986). Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis)*. *Ecology*, *67*(5), 1254–1269.

Naiman, R. J., Pollock, M., & Decamps, H. (1993). The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications*, *3*(2), 209–212.

NCEI. (2010). Summary of monthly normals for Elko Regional Airport, NV. from National Centers for Environmental Information, U.S. Department of Commerce, National Oceanic & Atmospheric Administration, National Environmental Satellite, Data, and Information Service

Neff, D. J. (1957). Ecological effects of beaver habitat abandonment in the Colorado Rockies. *The Journal of Wildlife Management*, *21*(1), 80–84.

Olmedo, G. F., Ortega-Farías, S., & de la Fuente-Sáiz, D. (2015). water: Tools and functions to estimate actual evapotranspiration using land surface energy balance models in R.

Paço, T. A., Pôças, I., Cunha, M., Silvestre, J. C., Santos, F. L., Paredes, P., & Pereira, L. S. (2014). Evapotranspiration and crop coefficients for a super intensive olive orchard. An application of SIMDualKc and METRIC models using ground and satellite observations. *Journal of Hydrology*, *519*, 2067–2080. https://doi.org/10.1016/j.jhydrol.2014.09.075

Pereira, J. S., & Chaves, M. M. (1995). Plant responses to drought under climate change in Mediterranean-type ecosystems. In *Global change and Mediterranean-type ecosystems*. New York: Springer-Verlag.

Perry, L. G., Andersen, D. C., Reynolds, L. V., Nelson, S. M., & Shafroth, P. B. (2012). Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America. *Global Change Biology*, *18*(3), 821–842. https://doi.org/10.1111/j.1365-2486.2011.02588.x

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J. M., Tucker, C. J., & Stenseth, N. C. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, *20*(9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011

Pollock, M. M., Beechie, T. J., & Jordan, C. E. (2007). Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. *Earth Surface Processes and Landforms*, *32*(8), 1174–1185. https://doi.org/10.1002/esp.1553

Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., & Volk, C. (2014). Using beaver dams to restore incised stream ecosystems. *Bioscience*, *64*(4), 279–290. https://doi.org/10.1093/biosci/biu036

Pollock, M. M., Castro, J., Jordan, C. E., Lewallen, G., & Woodruff, K. (2015). *The beaver restoration guidebook: Working with beaver to restore streams, wetlands, and floodplains*. (p. 189). Portland, Oregon, *Version 1.02*: United States Fish and Wildlife Service.

Polvi, L. E., & Wohl, E. (2012). The beaver meadow complex revisited—The role of beavers in post-glacial floodplain development. *Earth Surface Processes and Landforms*, *37*(3), 332–346. https://doi.org/10.1002/esp.2261

Porporato, A., Laio, F., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress III. Vegetation water stress. *Advances in Water Resources*, *24*, 725–744.

Rood, S. B., Patiño, S., & Coombs, K. (2000). Branch sacrifice: Cavitation-associated drought adaptation of riparian cottonwoods. *Trees*, *14*, 248–257.

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

Roy, D. P., Wulder, M. A., Loveland, T. R., Woodcock, C. E., Allen, R. G., Anderson, M. C., … Zhu, Z. (2014). Landsat-8: Science and product vision for terrestrial global change research. *Remote Sensing of Environment*, *145*, 154–172. https://doi.org/10.1016/j.rse.2014.02.001

Ruedemann, R., & Schoonmaker, W. J. (1938). Beaver dams as geologic agents. *Science*, *88*(2292), 523–525.

Sala, A., & Tenhunen, J. (1995). Simulations of canopy net photosynthesis and transpiration in Quercus ilex L. under the influece of seasonal drought. *Agricultural and Forest Meteorology*, *78*, 203–222.

Santos, C., Lorite, I. J., Allen, R. G., & Tasumi, M. (2012). Aerodynamic parameterization of the satellite-based energy balance (METRIC) model for ET estimation in rainfed olive orchards of Andalusia, Spain. *Water Resources Management*, *26*(11), 3267–3283. https://doi.org/10.1007/s11269-012-0071-8

Shafroth, P. B., Stromberg, J. C., & Patten, D. T. (2002). Riparian vegetation response to alterned disturbance and stress regimes. *Ecological Applications*, *12*(1), 107–123.

Sipple, W. S. (1992). Time to move on. *National Wetlands Newsletter*, *14*(2), 4–6.

Steinfeld, G., Letzel, M. O., Raasch, S., Kanda, M., & Inagaki, A. (2006). Spatial representativeness of single tower measurements and the imbalance problem with eddy-covariance fluxes: Results of a large-eddy simulation study. *Boundary-Layer Meteorology*, *123*(1), 77–98. https://doi.org/10.1007/s10546-006-9133-x

Stella, J. C., & Battles, J. J. (2010). How do riparian woody seedlings survive seasonal drought? *Oecologia*, *164*(3), 579–590. https://doi.org/10.1007/s00442-010-1657-6

Swanson, S., Wyman, S., & Evans, C. (2015). Practical grazing management to maintain or restore riparian functions and values on rangelands. *Journal of Rangeland Applications*, *2*, 1–28.

Trezza, R., Allen, R., & Tasumi, M. (2013). Estimation of actual evapotranspiration along the Middle Rio Grande of New Mexico using MODIS and Landsat imagery with the METRIC model. *Remote Sensing*, *5*(10), 5397–5423. https://doi.org/10.3390/rs5105397

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, *8*, 127–150.

USGS. (2016). National Water Information System data available on the World Wide Web (USGS Water Data for the Nation). Retrieved 4-07-2017, from US Geological Survey http://waterdata.usgs.gov/nwis/

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

Vivian, L. M., Godfree, R. C., Colloff, M. J., Mayence, C. E., & Marshall, D. J. (2014). Wetland plant growth under contrasting water regimes associated with river regulation and drought: Implications for environmental water management. *Plant Ecology*, *215*(9), 997–1011. https://doi.org/10.1007/s11258-014-0357-4

Westbrook, C. J., Cooper, D. J., & Baker, B. W. (2006). Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. *Water Resources Research*, *42*(6), n/a–n/a. https://doi.org/10.1029/2005wr004560

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., … Verma, S. (2002). Energy balance closure at FLUXNET sites. *Forest Meteorology*, *113*, 223–243.

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

Wright, S. J. (1991). Seasonal drought and the phenology of understory shrubs in a tropical moist forest. *Ecology*, *72*(5), 1643–1657.

Wright, S. J., & Cornejo, F. H. (1990). Seasonal drought and leaf fall in a tropical forest. *Ecology*, *71*(3), 1165–1175.

Zha, T., Barr, A. G., van der Kamp, G., Black, T. A., McCaughey, J. H., & Flanagan, L. B. (2010). Interannual variation of evapotranspiration from forest and grassland ecosystems in western Canada in relation to drought. *Agricultural and Forest Meteorology*, *150*(11), 1476–1484. https://doi.org/10.1016/j.agrformet.2010.08.003

How to cite this article: Fairfax E, Small EE. Using remote sensing to assess the impact of beaver damming on riparian evapotranspiration in an arid landscape. *Ecohydrology*. 2018; e1993. https://doi.org/10.1002/eco.1993