Title:
Unraveling groundwater contributions to evapotranspiration in a mountain headwaters: Using eddy covariance to constrain water and energy fluxes in the East River Catchment

Running Title:
Unraveling groundwater contributions to evapotranspiration…

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Abstract
Despite the importance of headwater catchments for western United States' water supply, these regions are often poorly understood, particularly with respect to quantitative understanding of evapotranspiration (ET) fluxes. Heterogeneity of land cover, physiography, and atmospheric patterns in these high-elevation regions lead to difficulty in developing spatially-distributed characterization of ET. As the largest terrestrial water flux behind precipitation, ET represents a significant fraction of the water budget for any watershed. Likewise, groundwater is the largest available freshwater store and has been shown to play a large role in the water balance, even in headwater systems. Using an eddy covariance tower in the East River Catchment, a Colorado River headwaters basin, this study estimates water and energy fluxes in high-elevation, complex systems to better constrain ET estimates and calculate overall water and energy budgets, including losses from groundwater. The eddy covariance method is used to estimate ET from years 2017 through 2019 at a saturated, riparian end-member site. Owing to complexities in near surface atmospheric structure such as stable boundary layers over snowpack and shallow terrain driven flow from surrounding landscape features, energy flux and ET estimates were limited to the warm season when energy closure residuals from the eddy-covariance system were reliably less than 30 %, a threshold commonly used in eddy covariance energy flux estimation. The resulting ET estimations are useful for constraining water budget estimates at this energy-limited site, which uses groundwater for up to 84 % of ET in the summer months. We also compared East River ET magnitudes and seasonality to two other flux towers (Niwot Ridge, CO and Valles Caldera, NM), located in the Rocky Mountains. This data is useful for constraining ET estimates in similar end-member locations across the East River Catchment. Our results show that groundwater-fed ET is a significant component of the water balance and groundwater may supply riparian ET even during low-snow years.

Key Words
Evapotranspiration, Eddy Covariance, Energy, Water, Fluxes, Headwaters

1. Background

Mountain headwater regions provide much of the world's water (Chang, Foster, Hall, Rango, & Hartline, 1982; Ikeda et al., 2010) and in the western United States, the Colorado River provides water for 30 million people and 4 million acres of irrigated agriculture (Reclamation, 2012). However, many western watersheds lose more water to the atmosphere through evaporation and transpiration (ET) than is discharged into rivers and streams (Knight, Fahey, & Running, 1981; Trenberth, Smith, Qian, Dai, & Fasullo, 2007). In the Western U.S., ET is often the second largest component of the water balance, after precipitation. ET is also associated with a catchment's energy balance making accurate estimations of this flux vitally important to overall water availability predictions (Healy, Winter, LaBaugh, & Franke, 2007) as well as regional energy budgets. Understanding how ET uses various water sources, and quantifying the amount of water each source is contributing to ET, leads to better water balance estimations in complex terrain. A recent study by Milly and Dunne (2020) estimates that the mean annual discharge of the Colorado River is decreasing due to increased evapotranspiration while another study shows similar trends in the Alps with an air temperature increase causing an increase in ET leading to a decrease in runoff consistent with a 3 % precipitation decrease (Mastrotheodoros et al., 2020). With headwaters systems in the western U.S. being increasingly under stress due to climate change (Pepin et al., 2015) and groundwater being an important resource even in mountain systems (Somers & McKenzie, 2020), it is critical to characterize these water balances more accurately.

Eddy covariance is a commonly used technique for quantifying latent heat—equivalent to ET multiplied by the latent heat of vaporization of water at a given temperature (Ceperley et al., 2017; Hirschi, Michel, Lehner, & Seneviratne, 2017; Maes, Gentine, Verhoest, & Miralles, 2019; Mamadou et al., 2014). This method computes the flux as the covariance between deviation from the mean of the vertical wind speed and deviation from the mean of the concentration multiplied by the air density (Burba, 2013; Swinbank, 1951). This method is effective in flat terrain with homogenous land cover due to the assumptions that must be made using this technique, including the lack of surface heterogeneity, adequate fetch, and turbulent fluxes (Burba & Anderson, 2006). Due to these assumptions, ET is challenging to quantify in headwaters regions as these regions are often marked by complexities such as heterogeneous land cover, large topographic gradients, and spatially varying atmospheric patterns. These heterogeneities often violate the assumptions commonly used for eddy covariance calculations. Due to these complexities, few studies have tested the effectiveness of measuring ET in complex headwaters regions (Flerchinger, Marks, Reba, Yu, & Seyfried, 2010).

Despite the challenges outlined above, some studies have successfully used the eddy covariance in high-elevation environments. Burns, Blanken, Turnipseed, Hu, and Monson (2015) studied how changes in precipitation affect the overall surface energy budget in a high-elevation forest while Frank, Massman, Ewers, Huckaby, and Negrón (2014) studied how disturbances, such as bark beetles, shift the energy balance components in the Rocky Mountains. Complimentary studies have also used eddy covariance in western riparian areas leading to helpful end-member ET values, which range from 10 to 30% surface energy balance closure error (Nagler et al., 2005; Scott et al., 2004; Scott et al., 2008; Wilson et al., 2002). Some studies have concluded that without including large-scale turbulent fluxes and accounting for all energy fluxes, some amount of closure error will persist—particularly in heterogeneous landscapes (Stoy et al., 2013; Foken, 2008; Georg et al., 2016). Despite the difficulty of obtaining full energy balance closure, small-scale estimations of ET can be useful for a better understanding of energy fluxes in mountain environments and result in data sets that can be used to check model performance.

Estimating the upper bound of ET is useful for understanding both the water and energy balance in complex mountain catchments. Similarly, understanding the source water for ET is also essential for better estimations of water availability and use, as the timing and magnitude of ET changes depending on the source water available. If precipitation is not a sufficient supply for ET, the plants will draw from deeper groundwater if it is available. Quantifying the groundwater contribution to ET allows for better estimates of ET across the catchment and subsequent estimations of available water and energy.

In this study, we improve upon the quantification of ET in high-elevation complex systems through the installation of an eddy covariance tower in the East River Catchment, we estimate groundwater contributions to ET at the flux tower location, we show the impact of variance in ET estimations and precipitation observations through water balance calculations, and we compare our results to other eddy flux sites in the Rocky Mountain region. Our study site, a catchment that contributes to the Upper Gunnison River Basin and eventually the Colorado

River, provides an archetype of other Rocky Mountain catchments. Our study period includes multiple water years characterized by both wet and dry conditions resulting in ET estimations useful for application across the entire catchment and to other headwaters regions. This study leads to greater understanding of water availability in headwaters systems, which can then be used for ecological and hydrological applications and downstream water planning.

2. Methods

2.1 East River Region

In our study, we installed an eddy covariance tower in the approximately 85 km^2 East River Catchment near Crested Butte, Colorado (38.922242, -106.949699). The East River is part of the headwaters of the Upper Gunnison River (a primary tributary to the Colorado River) which provides much of the flow to the Upper Colorado River Basin, and is a site typical of high-elevation watersheds with minimal human disturbance. Due to the catchment's influence on water availability in the west, it is a U.S. Department of Energy Scientific Focus Area (DOE-SFA) where many researchers are studying earth systems processes from the bedrock to lower atmosphere to better understand the hydrologic behavior mountain watersheds (Hubbard et al., 2018). It is a semi-arid, snowmelt-dominated catchment where much of the downstream water comes from the snow stored in these mountains during the winter. The catchment's land cover is highly heterogeneous (Figure 1) with about 38 % classified as shrub/scrub, 23 % as evergreen forest, 13 % as barren land, 11 % as deciduous forest, 7 % as grassland, and the remainder split between 10 other land cover types classified by the NLCD 2011 (Yang et al., 2018). The tower sits in a valley at an elevation of about 2800 m with mountain ridges and peaks on either side that reach about 3700 m in elevation. The East River runs through the valley next to the tower and the site is covered in snow for six months of the year and, if it is a wet year—defined as more than 750 mm of precipitation annually (Hubbard et al., 2018)—the ground is saturated for about one to two months in early summer. Based on well data located in the floodplain approximately 200 m from the tower location, the water table at the flux tower location never falls below 85 cm from the surface (Tokunaga et al., 2019; Figure 2).

Due to the complexities of eddy covariance inherent in mountain regions, we located the tower in a manner to minimize terrain influences, provide a consistent fetch, and capture the upper-bound floodplain ET behavior (Figure 1b,c,d). The tower was oriented so that it would mainly capture turbulence coming from the dominant, northwestern (up-valley), wind direction. The tower captures the turbulence from this direction about 70 % of the time (Figure 3). The valley also gives saturated, end-member observations as evidenced by the soil moisture data collected at the flux tower site throughout the study period, which shows the subsurface is saturated, has standing water or is near saturation for large fractions of the year (Figure 4). Observations at this nearly saturated end-member site allow us to constrain or "bound" the upper value estimates of latent heat flux in the catchment, given that this area is likely the area with the least amount of moisture limitation and possibly the greatest potential values of ET.

2.2 Eddy Covariance Tower Instrument Details

The eddy flux tower, shown in Figure 1, stands at six meters high and supports multiple sensors. The sensor suite for the eddy covariance (EC)/energy balance system are provided in Table 1 and include air temperature and humidity sensors, a 4-way (incoming and outgoing, short and longwave) radiometer, a snow depth sensor, an air pressure transducer, a three-dimensional sonic anemometer with integrated CO_2 and H_2O open-path gas analyzer, two levels of soil moisture, soil temperature and soil electrical conductivity (5 cm and 25 cm), and ground heat flux plates located at a 5 cm depth. The measurement height for the eddy covariance/infra-red gas analyzer and 4-way radiometer was set at just below 6 m (5.9 m) which is approximately 3-4 m above the grass and willow/shrub gallery that covers much of the valley floor.

Converting raw, high-frequency measurements of wind speed and direction, temperature, and water vapor and carbon dioxide concentrations into time-averaged energy and scalar flux estimates involved a number of processing steps. The theoretical foundation for estimating fluxes using the eddy covariance method is detailed in Swinbank (1951) and in Shuttleworth (2012) and numerous flux data processing codes have been created. Here we use the open source, EasyFlux-PC software created and distributed by Campbell Scientific (Campbell Scientific, 2016) and follow AmeriFlux guidelines (Aubinet, Vesala, & Papale, 2012) for flux data processing and output sharing. The EasyFlux-PC code has many standard and user-specified options for processing and quality-controlling flux estimates. The tower and canopy specifications as well as the flux processing options are listed in Table 2. The flux data processing options used included measurement value filtering and despiking (Mauder & Foken, 2004), the planar-fit wind coordinate rotation method of Wilczak, Oncley, and Stage (2001), low-pass filter spectral correction (Massman, 2001), sonic temperature correction for humidity effects (van Dijk, Kohsiek, & DeBruin, 2004), air density fluctuations (WPL method of Webb, Pearman, & Leuning, 1980), lag CO_2 and water vapor versus wind corrections (Horst & Lenscschow, 2009; Foken, 2012), and additional quality control checks (Foken, 2003).

Final data is output in 30-minute time increments. Data was then checked for reasonableness and missing time stamps are added and the latent heat data was gap-filled by taking the linear average of the surrounding latent heat values. The latent heat was then multiplied by the latent heat of vaporization to get an estimate of evapotranspiration. Ground heat flux is measured with the ground heat flux plates and net radiation is calculated from the shortwave and longwave radiation that is measured by the 4-way radiometer. Using these variables, we can calculate the energy balance closure error, which was also assessed as a means of filtering out periods of incorrect or otherwise unreliable data. In this study, we have analyzed the data from April 15, 2017 to September 27, 2019. Details on closure analysis are provided below in Sections 2.3 and 3.1.

2.3 Energy Budget Partitioning

The amount of energy going into the system should be offset by the amount of energy used by the system; therefore, the net radiation into the system should be accounted for by the total heat fluxes of the system:

$$Rn - G = LE + H + i, \qquad \text{Eq. 1}$$

where Rn is the net radiation, G is the ground heat, LE is the latent heat, H is the sensible heat, and i is the source/sink term with all components in W/m^2. We conducted an energy balance closure calculation on all three water years of data. We considered errors less than 30 % to represent good closure, meaning at least 70 % of the net radiation is accounted for by ground, sensible, and latent fluxes. Given that we are not measuring the thermal energy in the snowpack, of the water that pools on the surface just after snowmelt, of the vegetation canopy or canopy airspace or other energy exchange processes, along with the atmospheric complexities of mountain environments (Finnigan, 2004), 30 % is a realistic closure estimate. This closure error percentage is consistent with previous riparian and mountain area studies that resulted in closure errors of 10 to 30 percent (Eshonkulov et al., 2019; Nagler et al., 2005; Scott et al., 2004; Scott et al., 2008; Wilson et al., 2002).

We took the 24-hour average of the eddy covariance data and calculated the closure error percentage for each 24-hour period as:

$$\%\, closure\ error = \frac{(Rn-G)-(LE+H)}{Rn} * 100 \qquad \text{Eq. 2}$$

This daily closure error was then averaged to monthly closure error (Figure 5) for seasonal analysis. The closure error is generally smaller in spring and summer months than in winter months. Months with negative closure mean the combined latent, ground, and sensible heat fluxes are greater than the radiation.

2.4 Summer Flux Comparisons

Most of the annual ET occurs over the summer months (Table 3), and closure errors are lowest during these times, so we compared datasets of summers (June-August) 2017, 2018, and 2019 to understand the interannual variability of ET and precipitation. We averaged latent heat, total net radiation (Rn-G), air temperature, and dewpoint depression for each summer using the same dates for all variables across each summer. We calculated ET (latent heat flux multiplied by the latent heat of vaporization) for all three summers along with the total ET for the water year (water year 2017 is shortened and begins when we installed the tower in April, 2017). The total precipitation for each water year was obtained from a precipitation gage (Billy Barr station) located within the East River Catchment at an elevation approximately 200 m higher and 6.2 km northwest of the flux tower.

2.5 Groundwater Fed ET

Given the magnitude and timing of precipitation and ET, we hypothesize that ET is drawing from groundwater during the drier summer months. The contribution of snow melt water and summer rainfall (monsoon) to ET are often considered when analyzing ET source water. However, groundwater may also be a large contributor to ET in May through September. There is evidence that plants not only use direct snow melt and rainfall for transpiration, but also access groundwater, particularly during this time in mountain systems (Bearup, Maxwell, Clow, & McCray, 2014).

Using an equation from Scott et al. (2008) (Equation 3), we estimated how much ET comes from groundwater at the flux tower location over the summer (May-September) for years 2017, 2018, and 2019 as follows:

$$ET_{gw} = ET - (P - d\theta), \qquad \text{Eq. 3}$$

where ET_{gw} is ET from groundwater, ET is total evapotranspiration, P is precipitation, and $d\theta$ is the change in soil moisture in the top 30 cm of soil from May to September. ET was gap-filled by taking the linearly-averaged latent heat values of the days surrounding the missing data. These latent heat values were then converted to ET using the latent heat of vaporization. We accounted for days where precipitation occurs, which would make the ET less than the linear average of the surrounding days. Runoff is assumed to be negligible since we are calculating ET_{gw} over the small and relatively flat area of the eddy flux tower. Positive ET_{gw} indicates ET is greater than precipitation and soil moisture change, and therefore ET is likely drawing from groundwater.

2.6 Water Balance Across the East River Catchment

To better understand the variability in precipitation and ET across the entire catchment over the three water years, we calculated the water balance at the East River valley location (located near the outlet of the catchment) using the equation,

$$residual = P - ET - Q - d\theta, \text{ Eq. 4}$$

where ET is total evapotranspiration, P is precipitation, Q is the runoff at the outlet of the East River Catchment co-located with the flux tower (Carroll & Williams, 2019), and $d\theta$ is the change in soil moisture in the top 30 cm of soil. For water year 2017, ET is only available for April 15 through September 30. For the remaining water years, ET is available for the full water year. All ET data gaps have been filled using the method described in subsection 2.5. We assume that the flux tower ET value is representative of the entire catchment. Though we picked a wet site as an upper bound ET estimate, we are using these values as representative for the whole catchment in order to understand the potential variability in the water balance across the catchment. These ET values likely do not represent ET across the entire basin, but they can be used for end-member variability analysis. To represent potential variability in ET, we use both the gap-filled data as well as the non-gap-filled data to understand the effects of the range in ET values on the water balance. Q is calculated for the full water years based on the catchment area of 85 km^2. P represents the three full water years and we used values from both the Billy Barr meteorological station as well as from the Schofield SNOTEL station located at the northern edge of the catchment at approximately 3260 m in elevation and 13.4 km northwest of the flux tower and discharge outlet (Natural Resources Conservation Service, 1984). Using both of these precipitation gages gives us an understanding of how variance in precipitation affects the water balance residual. We also calculated an effective precipitation at each station to account for sublimation from the canopy, surface, and blowing snow, which is not captured by the flux tower. We left the summer precipitation unchanged and removed 28 % of precipitation in the winter based on the percentages of winter sublimation values in open, forested, and alpine sites by Sextone et al. (2018). θ is equal to the values found in Section 2.5. Therefore, we have four different water balance calculations for each year using two different precipitation values (Billy Barr and Schofield) and two different ET values (gap-filled and non-gap-filled).

2.7 Comparisons of East River Catchment to Other Flux Towers

To put our estimates of ET across the East River catchment into a regional context, we compared the results of our tower to those from two other flux towers. First, we compared our eddy flux estimates with those from another flux tower in the central Rocky Mountain region, operational since 1998, located at the Niwot Ridge AmeriFlux site (US-NR1) in Colorado about 174 km northeast of the East River Catchment (Burns et al., 2015; Monson et al., 2002) (Figure 6). We obtained the data from the Niwot Ridge AmeriFlux website for years 2017 through 2019 (https://ameriflux.lbl.gov/doi/AmeriFlux/US-NR1). The daily ET values at the East River site compare well with those at Niwot Ridge with both locations having obvious seasonal cycles with ET increasing as the snow melts in the spring, reaching a peak in summer, and decreasing as both water and energy availability decrease in the fall and winter. ET is greatest during the summer of 2018, followed by summer 2017, then 2019 in the East River location. Both locations are high-mountain environments, though the East River has more heterogeneous land cover, as

Niwot Ridge is characterized by an expansive evergreen needleleaf forest, and the East River has greater sustained water availability throughout the year as the flux tower sits in a saturated valley 300 m lower than the Niwot Ridge tower.

We also compared the East River data to the Valles Caldera AmeriFlux tower (US-Vcp) (Table 4) located in southern Rocky Mountain region in north-central New Mexico in the Jemez River Basin. This site is characterized by Ponderosa Pine and Gambel Oak and sits below the flux tower at an elevation of 2500 m (Litvak, 2007). A favorable comparison of the fluxes from the East River site against these other sites in the region provide confidence in using the East River ET estimates for broader water budget investigations within the East River basin. The results of these comparisons follow in the next section.

3. Results and Discussion

3.1 Energy Balance Closure

The month with the least closure error is March 2018 followed by August 2017, with closure errors of 0.163% and 3.39%, respectively (Figure 5). In March 2018, net radiation is low and correspondingly, the heat fluxes are small which appear to contribute to a small closure error percentage. The winter of 2018 was also a dry year with minimal snowpack, which could also contribute to this smaller closure error. When the ground is saturated it is possible that some of the energy penetrating the ground surface is used to heat water that runs off into the stream leaving some energy fluxes unaccounted for by the tower. Once the ground is no longer saturated and the snowpack is gone, incoming energy can contribute more directly to the measured heat flux terms in Eq. 2.

These results also show that summer closure error is lower, on average, than fall and winter closure error. In winter, the site is covered in snow and a comparatively stable planetary boundary layer (PBL) persists, which creates smaller eddies and more laminar flow which are more difficult for eddy covariance sensors to measure heat fluxes (Baldocchi, Hinks, & Meyers, 1988; Eshonkulov et al., 2019).

We conducted a footprint analysis to ensure the flux tower is measuring turbulence from a reasonable location and distance. We used the Flux Footprint Prediction method (Kljun, Calanca, Rotach, & Schmid, 2015) to estimate the warm season average flux footprint (Figure 7). To calculate the footprint, we used values typical of the warm season, including a roughness length of 0.0879 m, a planetary boundary layer (PBL) height of 2000 m, an Obukhov length of 254.31 m, a standard deviation of lateral velocity fluctuations of 0.578 ms^{-1}, and a friction velocity of 0.28 ms^{-1}, and a wind direction of 297 degrees. The footprint extends approximately 140 m in the northwest direction (80 % of the fluxes originate within the 140 m), which aligns with the predominant wind direction, and increases our confidence in summer flux estimations. During the winter months, a more stable PBL and more laminar flow regime will likely result in a much greater flux measurement sampling area or “footprint” which may come from hillslope or other non-riparian areas. Prevailing winds are also much stronger during the winter time, particularly during storm events, which may also contribute to enlargement of the flux tower footprint.

Lastly, we are not explicitly accounting for the thermal energy stored in the snowpack, nor within standing water under the tower, which would be absorbing (or releasing) energy and is therefore unaccounted for by the tower measurements. Combined, the closure error results show that the energy flux estimates are less reliable in the winter as the closure error is much larger and all of the energy in the system is not accounted for by the heat fluxes or there is more energy in the form of heat fluxes than is accounted for by incoming net radiation. Therefore, our analyses focus predominantly on the warm season flux characteristics.

3.2 Summer Energy and Water Flux Comparisons

To better understand our ET estimates within the context of overall watershed or regional water budgets, we need to understand the temporal patterns of ET and precipitation during the three summers. Average latent heat flux is greatest during the summer 2017 with summer 2018 having the lowest average latent heat flux (Table 3). The table shows that the differences between summers of available energy, ET, latent heat, and air temperature are much less across the three summers than the differences in precipitation. 2019 had the greatest precipitation with the year of lowest precipitation, 2018, being about 325 mm less. Total annual ET does not follow the same temporal patterns as annual precipitation with the largest ET value occurring during the lowest precipitation year. Similar to the findings of Scott et al. (2008), ET in this riparian area is not as variable as precipitation over the three study years. While precipitation varies by 30 % across the three years, ET varies by only 16 % suggesting that precipitation is not the primary driver (or limiter) of ET in this system, supporting the hypothesis that this site behaves as a mostly saturated end-member site, which is not water-limited for ET.

We then compared these summers on a time series (Figure 8). All three summers have generally similar monthly patterns and magnitudes of ET (Figure 8b) showing overall site consistency across three water years despite large differences in precipitation. However, the year with the maximum ET value in each month is not always the same as the year with the maximum soil moisture value at both 5 cm and 25 cm below the surface (Figure 8c,d). For example, we see that May and June respond to snowmelt with the highest average soil moisture in 2019 (Figure 8c,d), while ET for May and June of 2019 is the lowest of the three summers (Figure 8b). Available energy also does not perfectly follow the patterns seen in ET across the three years (Figure 8a). The years with greatest average monthly available energy do not always result in years with the greatest average monthly ET. Given that maximum ET and soil moisture values for a given year do not always correspond with each other, we can hypothesize that ET comes not just from shallow soil moisture, but is also supplemented by deeper groundwater. This deeper groundwater seems to supplement soil moisture as a source of plant available water, shown by the lower seasonal variability at 25cm than 5cm. Not only is ET drawing from this supplemented moisture, but also from the deeper groundwater itself.

3.3 Summer Groundwater Contributions to ET at Flux Tower Location

An estimation of the amount of groundwater used to supplement ET during the drier months at the flux tower site is useful for understanding the quantity of ET not supplied by precipitation, which then helps us estimate the amount of total ET in a given year. ET_{gw} values for all three summers are positive indicating that groundwater supplies a fraction of ET regardless of precipitation (Figure 9). ET drew most heavily from groundwater in the summer of 2017 (83.9 %) closely followed by 2019 (83.5 %), with the summer of 2018 having the least amount of groundwater use (18.6 %). While 2018 had the least precipitation annually (Table 3), much of the annual precipitation occurred during the summer months leading to less ET, but also less groundwater use than the other two summers, showing a reliance on rainwater for summer 2018 rather than a reliance on groundwater due to snowmelt. These summers offer insight into the variability of ET groundwater use across water years.

Though the magnitude of precipitation is crucial for ET, the timing of precipitation across the year dictates whether ET needs to draw from groundwater as in 2017 and 2019 when ET seems to use water from snowmelt, or whether ET coincides with summer rain as in the case of 2018. This shift in water sources is suggested by simulations (Bearup et al., 2014; Kollet & Maxwell, 2008; Maxwell & Condon, 2016; Maxwell, Condon, Danesh-Yazdi, & Bearup, 2019). Water table data from a nearby well located approximately 200 m from the flux tower also confirms that vegetation would have access to groundwater during these summer months along the riparian flood plain (Tokunaga et al., 2019; Figure 2).

Without access to groundwater, ET values would likely decrease substantially in 2017 and 2019 as the only contributing water, we estimate, would be from precipitation and shallow soil moisture resulting in 71.82 mm and 65.21 mm of ET for summers of 2017 and 2019, respectively. These ET values are likely closer to what we might expect as low end-member ET at higher elevations in uplands and on ridge tops where land-surface energy processes may be disconnected from groundwater (Kollet & Maxwell, 2008; Maxwell & Kollet, 2008, Missik et al, 2018; Szilagvi, Zlotnik, & Jozsa, 2013) and may not have as much access to groundwater as the flux tower location, which sits in a convergent zone. While subject to uncertainty, these estimates indicate that groundwater may increase ET values by up to 84 % making it critical to better constrain these higher elevation water fluxes. As soil structure and soil moisture conditions vary across the East River Catchment it is important to provide additional observations of ET to constrain this variability.

3.4 Water Balance Estimations for the Catchment

Though the flux tower is useful in developing quantitative estimates ET in complex, headwaters settings, ET remains an uncertain variable in larger scale, watershed water balances. Calculating the water balance using ET from this site results in upper-end estimates of the water balance in the catchment and may be similar to maximum ET lost in similar regional catchments. When ET is gap-filled using the procedure outlined in Subsection 2.5 above, we see an increase in ET compared to that of non-gap-filled ET, of 17 %, 22 %, and 13 % for water years 2017, 2018, and 2019, respectively (Figure 10). This increase in ET has significant impacts on the residual of the water balance, increasing the residual when the system is losing water and decreasing the residual when the system is gaining. This variability highlights the importance of correctly gap-filled ET for accurate water balance estimates.

This variability can also be seen in the precipitation. In 2017, the Billy Barr station records precipitation that is approximately 53 % of what is registered at the Schofield station (a difference of 663.11 mm) while 2019 similarly has a difference of 555.48 mm or 59 % of precipitation. This range in precipitation amounts over a fairly short distance has been well-documented and is due in large part to the complex terrain. This spatial variability in precipitation could have large consequences as it alters the amount of water available in the system depending on the station used for water balance calculations.

Uncertainty in the spatial variability of precipitation and in ET estimations is evident in the residuals of the calculated water balance for the catchment. When using Billy Barr precipitation in 2017, the system is operating at a water deficit or loss (Figure 10a,b). However, when we use Schofield precipitation that same year, the system is gaining water for both the non-gap-filled and gap-filled ET values (Figure 10c,d). Though water years 2018 and 2019 are both in a water deficit, the difference in the amount of water lost is large between using Billy Barr precipitation and Schofield precipitation regardless of ET estimations. The difference in residuals when using the non-gap-filled ET as opposed to the gap-filled ET is 66.13 mm, 98.48 mm, and 54.79 mm for water years 2017, 2018, and 2019, respectively at both Billy Barr and Schofield. This increase in ET using the gap-filled values leads to greater water usage and a decline in the residual resulting in less water available per year.

The variability in residuals due to variability in precipitation and ET has large implications for water balance estimations and water use in the East River Catchment. If the water balance shifts by 55 mm to 100 mm per year based on ET estimations, these estimations become vitally important for water availability estimations. We also only have ET estimations at one location in the catchment, which is not very near either of the precipitation gages. The precipitation data is equally important as it can swing the catchment from a gaining system when using one set of data to a losing system when using data from another location as seen in the residuals from 2017, which was considered a wet year for this basin (Table 5). This variability makes the water balance difficult to estimate across the entire East River Catchment without access to more data highlighting the need for meteorological stations for precipitation and eddy covariance towers for ET estimations to constrain the variability in these fluxes.

3.5 Comparisons of Regional ET Estimates

The Valles Caldera has the greatest ET both annually and seasonally across all three years of study. Valles Caldera receives the least amount of cumulative precipitation across the three years, but this location has the greatest energy input, shown in the largest temperatures, leading to larger ET values. East River ET is the next largest for summer (June-August) ET in all years; however, Niwot Ridge annual ET is greater than East River ET in 2019 while East River annual ET is greater in 2017 and 2018. Niwot Ridge had the greatest annual ET in 2019 while the summer ET was greatest in 2017. In 2019, Niwot Ridge had lower overall summer values, but they remained consistent from April to September making 2019 the year with the largest annual ET at Niwot Ridge, whereas 2017 experienced larger summer values with lower values in the surrounding months making 2017 the year with the largest summer ET. The East River followed a similar pattern with greatest summer ET occurring in 2017 while greatest annual ET was in 2018. May and September of 2018 both contribute larger ET values making the overall year greatest in ET. The Valles Caldera experienced the greatest annual and summer ET during the same year, 2019.

The maximum summer ET values seem to correspond to the years with greatest precipitation at the two sites outside of the East River. Both Valles Caldera and Niwot Ridge seem to be moisture limited sites with the amount of precipitation and available water dictating the maximum ET in the dry summer months, whereas the East River site is more dependent on energy as it is located in a near-saturated end-member location with access to groundwater for

ET supplementation and variations in precipitation have less effect on ET than variations in energy.

4. Future Study

Given the existence of only one flux tower in the East River Catchment, more measurements from additional locations are needed to draw firm conclusions about the dynamic range of ET values across the rest of the catchment and across all seasons. The data from both the Niwot Ridge and Valles Caldera flux towers give us some insight into how ET may be behaving across other locations throughout the East River basin. The Niwot Ridge site is useful in helping to quantify ET at higher elevations in the East River Catchment during the summer months. These high-elevation locations are often marked by evergreen needleleaf land cover, greater wind speeds, lower temperatures, and lower soil moisture. We hypothesize that ET is lower at higher elevations in the East River Catchment—more closely resembling values from Niwot Ridge—than the riparian area where the flux tower currently sits. While we would expect ET to be similar to the Valles Caldera values at lower elevations with greater radiation; the location of the East River eddy flux tower sits at one of the most saturated and lowest elevations locations within the East River Catchment. Therefore, we expect the rest of the basin ET to be less than or equal to the measured East River ET flux values.

This site comparison helps constrain ET not only across the East River Catchment leading to a better understanding of water availability, but also across the rest of the Rocky Mountains. The East River flux tower offers useful information at a highly heterogeneous, yet vital, headwaters region about energy and water fluxes that differs from two other currently operational AmeriFlux and/or FLUXNET sites in the Rocky Mountains, Valles Caldera and Niwot Ridge. Understanding the high, end-member ET values allow for estimations to be made across the rest of the catchment and Rocky Mountains leading to better understanding of water availability in historically underrepresented, complex locations. These flux tower comparisons also highlight the need for more direct measurements of ET and energy fluxes in these heterogeneous mountain environments. End-member analysis is useful for constraining the higher end of ET in the East River Catchment; however, a larger number of flux towers at diverse locations across the basin—and other regions of the Rocky Mountains—would ensure better water and energy availability estimations useful for downstream planning.

5. Conclusions

This study uses an eddy flux tower in a complex terrain, high-elevation, riparian valley to provide critical insight into land surface energy fluxes and ET. Estimates of the land energy balance from our site resulted in measurement time periods with less than 30 % closure error in the spring and summer months showing that most of the energy coming into the system can be quantified and partitioned between latent, ground, and sensible heat fluxes. The closure error found here is within the ranges found at other study sites in mountain regions and riparian areas of 10 to 30 % closure error (Eshonkulov et al., 2019; Nagler et al., 2005; Scott et al., 2004; Scott et al., 2008; Wilson et al., 2002) and the daily ET values for the range of the study period are similar in magnitude to those found at the Niwot Ridge AmeriFlux site (about 0 to 5 mm/day), another high, continental montane ecosystem. The closure error that prohibited use of some the EC data is expected to decrease if snowpack energy flux during stable, winter conditions and the energy involved in heating standing water prior to surface runoff were also measured.

We show that in a saturated end-member site, summer ET is likely groundwater fed and will not be as variable as precipitation and also that recent or prior winter precipitation is not always the main driver of ET, as it may be in other Rocky Mountain locations. This site is not water-limited and thus is useful for constraining upper-end estimates of ET for the rest of the East River Catchment and is behavior that may be applicable across other western US headwater catchments for constraining ET estimations.

Using precipitation, change in soil moisture, and ET values, we can estimate groundwater contributions to ET showing that groundwater may increase ET values by up to 84 % (though other water sources may also contribute to this ET deficit). This shows the necessity in constraining these variables at high-elevation catchments and additional observations are needed to better estimate ET from groundwater across the rest of the East River Catchment.

Both precipitation and ET are highly variable across the catchment. The variability between non-gap-filled and gap-filled ET illustrates the challenges in constraining the overall catchment water budget. The variability in precipitation can change a wet year from a system of water excess into a system of water deficit creating complications for estimating water availability and planning downstream water consumption. The high spatial variability in precipitation, and likely in ET, suggests that additional observations are needed to more confidently close the water budget; however, our water balance estimates provide a potential maximum estimate of ET across the catchment.

Comparison of the East River eddy flux estimates with those from two other eddy flux towers in the Rocky Mountains help constrain ET across the rest of the East River Catchment and other similar mountain headwater regions. Given that this site is likely an end-member, we would expect ET values across the East River Catchment to be equal to or less than those at the eddy flux location. ET at higher elevations may be similar to the magnitudes of ET seen at Niwot Ridge given the similarities between Niwot Ridge and the high-elevation locations in the East River Catchment.

The ability to quantify these fluxes, particularly ET, is useful for estimating water availability downstream from headwaters catchments. Though this study presents a useful dataset for water and energy fluxes in complex headwater regions, access to more eddy covariance data in diverse locations across the basin and with longer periods of record, would allow for better estimations of ET and other water and energy fluxes across an entire catchment leading to better water availability predictions that are useful for downstream water planning.

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Data Availability Statement

All data from this study will be made openly and publicly available through the Watershed Function ESS-DIVE community repository: https://data.essdive.lbl.gov/data/query=Watershed%20Function%20SFA upon publication. In additional to being assigned a DOI, all metadata will be included to ensure that these data are FAIR: Findable, Accessible, Interoperable and Reproducible.