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Evapotranspiration response to multiyear dry periods in the semiarid western United States

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Abstract
Analysis of measured evapotranspiration shows that subsurface plant-accessible water storage (PAWS) can sustain evapotranspiration through multiyear dry periods. Measurements at 25 flux tower sites in the semiarid western United States, distributed across five land cover types, show both resistance and vulnerability to multiyear dry periods. Average (±standard deviation) evapotranspiration ranged from 660 ± 230 mm yr⁻¹ (October–September) in evergreen needleleaf forests to 310 ± 200 mm yr⁻¹ in grasslands and shrublands. More than 52% of the annual evapotranspiration in Mediterranean climates is supported on average by seasonal drawdown of subsurface PAWS, versus 29% in monsoon-influenced climates. Snowmelt replenishes dry-season PAWS by as much as 20% at sites with significant seasonal snow accumulation but was insignificant at most sites. Evapotranspiration exceeded precipitation in more than half of the observation years at sites below 35°N. Annual evapotranspiration at non-energy-limited sites increased with precipitation, reaching a mean wet-year evapotranspiration of 833 mm for evergreen needleleaf forests, 861 mm for mixed forests, 558 mm for woody savannas, 367 mm for grasslands, and 254 mm for shrublands. Thirteen sites experienced at least one multiyear dry period, when mean precipitation was more than one standard deviation below the historical mean. All vegetation types except evergreen needleleaf forests responded to multiyear dry periods by lowering evapotranspiration and/or significant year-over-year depletion of subsurface PAWS. Sites maintained wet-year evapotranspiration rates for 8–33 months before attenuation, with a corresponding net PAWS drawdown of as much as 334 mm. Net drawdown at many sites continued until the dry period ended, resulting in an overall cumulative withdrawal of as much as 558 mm. Evergreen needleleaf forests maintained high evapotranspiration during multiyear dry periods with no apparent PAWS drawdown; these forests currently avoid drought but may prove vulnerable to longer and warmer dry periods that reduce snowpack storage and accelerate evapotranspiration.

KEYWORDS
drought resistance, drought response, evapotranspiration, flux tower, plant-accessible water storage
1 | INTRODUCTION

Mountain watersheds supply approximately two-thirds of freshwater in arid regions, serving as an essential or supportive water source for approximately 44% of the global population (Viviroli, Du, Messerli, Meybeck, & Weingartner, 2007). The complex topography, steep temperature and precipitation gradients with elevation, high interannual climate variability, and heterogeneous vegetation distribution in these watersheds limit our ability to accurately estimate and represent major components of the hydrologic cycle (Bales et al., 2006). Multiyear dry periods are arguably the most complex yet least understood natural hazard, with slow progression and long-term socioeconomic effects (Cancelliere, Di Mauro, Bonaccorso, & Rossi, 2007; Mishra & Desai, 2005). Gaps in knowledge of drought resistance exacerbate the impacts of multicyr dry periods by impeding anticipatory planning and operational water resources management decisions (Modarres, 2005). Gaps in knowledge of drought resistance exacerbate the impacts of multicyr dry periods by impeding anticipatory planning and operational water resources management decisions (Modarres, 2005). Gaps in knowledge of drought resistance exacerbate the impacts of multicyr dry periods by impeding anticipatory planning and operational water resources management decisions (Modarres, 2005). Gaps in knowledge of drought resistance exacerbate the impacts of multicyr dry periods by impeding anticipatory planning and operational water resources management decisions (Modarres, 2005). Gaps in knowledge of drought resistance exacerbate the impacts of multicyr dry periods by impeding anticipatory planning and operational water resources management decisions (Modarres, 2005).

Evapotranspiration accounts for the majority of water leaving a semiarid region watershed (Bales et al., 2006), and the timing and magnitude of precipitation and evapotranspiration govern basin runoff. Evapotranspiration is challenging to measure directly at individual sites and shows high spatial heterogeneity with water availability, temperature, vegetation type, and vapour pressure variability (Vieissman & Lewis, 2003). Many drought assessments either supplement actual evapotranspiration with potential evapotranspiration (PET) or develop an index that is based largely on precipitation. Poor correlation in the interannual variability of precipitation and evapotranspiration (Oishi, Oren, Novick, Palmroth, & Katul, 2010) and the often weak relationship between evapotranspiration and temperature in water-limited regions can lead to misrepresentation of evapotranspiration (McAfee, 2013). The evapotranspiration response to drought varies significantly with vegetation type (Vicente-Serrano et al., 2013); this variation is generally unaccounted for in PET-based indices and underscores the need to consider actual evapotranspiration when assessing drought stress across landscapes (Bales et al., 2018).

Subsurface plant-accessible water storage (PAWS) capacity has been defined as the amount of subsurface water that is accessible for extraction by roots (Klos et al., 2018). This reservoir of water sustains evapotranspiration during periods when evapotranspiration exceeds precipitation and is important both seasonally and during multicyr dry periods (Bales et al., 2011, 2018). A second water store, seasonal snowpack, extends the period that subsurface PAWS is replenished after precipitation ends (Oroza, Bales, Stacy, & Glaser, 2017). This can be especially important for locations with long summer dry periods such as California’s Sierra Nevada, where the snow cover period averages 2–3 weeks longer for each 300-m increase in elevation, reflecting both more precipitation and later melt (Bales, Rice, & Roy, 2015; Rice, Bales, Painter, & Dozier, 2011). The spatial response of evapotranspiration to the cumulative depletion of subsurface PAWS during multicyr dry periods, and of the effect of reduced snowpack storage on PAWS depletion as climate warms, are not well known.

Advances in technology have improved our ability to quantify components of the hydrologic cycle as well as examine and monitor the impacts of multicyr dry periods. The growing network of eddy covariance flux towers provides direct measurements of the land–atmosphere fluxes of water, carbon, and energy. Eddy covariance data have been used to examine drought in Canadian boreal forests (Zha et al., 2010) and scaled to assess drought impacts across river basins in the western United States (Bales et al., 2018). Precipitation and evapotranspiration time series can be combined to infer the seasonal and multicyr net drawdown of PAWS (Fellows & Goulden, 2016).

We combined multicyr records of precipitation with evapotranspiration records measured by eddy covariance to estimate the PAWS drawdown at tower sites across the semiarid western United States. These measurements were compared across and within vegetation types and climatic regimes to address three questions. First, how do annual values and seasonal trends of evapotranspiration vary by climate and land cover type? Second, what amount of annual dry-season evapotranspiration is supported by the seasonal drawdown of PAWS, and how does this vary by climate and land cover type? Third, how much PAWS is available to support evapotranspiration during multicyr dry periods?

2 | METHODS

We used existing eddy covariance datasets to assess the effects of multicyr dry periods on measured evapotranspiration. We defined multicyr dry periods as three or more consecutive years having a mean dry-period annual precipitation at least one standard deviation below the site’s historical mean. Evapotranspiration and temperature data from eddy covariance flux towers were compiled and processed along with site characteristics. Precipitation data for the sites were obtained from a variety of sources. We used daily and monthly evapotranspiration and precipitation data during the dry season to quantify the fraction of annual evapotranspiration that is supported by subsurface PAWS. We also calculated the net long-term drawdown of subsurface PAWS before any attenuation of evapotranspiration was observed during multicyr dry periods. Finally, we looked at how snowpack storage affects the seasonal evapotranspiration dependency on PAWS and how this may change with a shift from snow to rain.

2.1 | Study area

This study focused on sites in the western United States, in and near the Sierra Nevada, Rocky, San Jacinto, Jemez, and Santa Catalina mountains. The study area is bounded by latitudes 31.75–43.15°N and longitudes 121.00–105.60°W (Figure 1). These areas are categorized as semiarid to arid, with mean annual (October through September) precipitation ranging from 139 to 1,341 mm per year and average annual temperatures ranging from −0.9 to 23.3°C (Table 1). The study sites have an elevation range of 129 to 3,190 m above mean sea level and include evergreen needleleaf forests, mixed forests, woody savannas, grasslands, and shrublands.
FIGURE 1  Flux tower locations. Colour codes and different markers represent land cover types. The background is the International Geosphere-Biosphere Programme (IGBP) layer for the region

TABLE 1  Sites characteristics. The IGBP land cover types are evergreen needleleaf forests (ENF), mixed forests (MF), woody savannas (WSA), grasslands (GRA), and shrublands (OSH)

<table>
<thead>
<tr>
<th>Site</th>
<th>Site abbreviations</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation, m</th>
<th>Mean precipitation, mm</th>
<th>Mean evapotranspiration, mm</th>
<th>Mean temp, °C</th>
<th>IGBP</th>
<th>Period of record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blodgett Forest</td>
<td>US-Blo</td>
<td>38.90</td>
<td>−120.63</td>
<td>1,315</td>
<td>1,341</td>
<td>892</td>
<td>11.4</td>
<td>ENF</td>
<td>1998–2007</td>
</tr>
<tr>
<td>Mount Bigelow</td>
<td>MB</td>
<td>32.42</td>
<td>−110.73</td>
<td>2,583</td>
<td>720</td>
<td>718</td>
<td>9.6</td>
<td>ENF</td>
<td>2010–2015</td>
</tr>
<tr>
<td>Valles Caldera Ponderosa Pine</td>
<td>US-Vcp</td>
<td>35.86</td>
<td>−106.60</td>
<td>2,495</td>
<td>457</td>
<td>704</td>
<td>6.5</td>
<td>ENF</td>
<td>2008–2014</td>
</tr>
<tr>
<td>Providence</td>
<td>US-CZ3</td>
<td>37.07</td>
<td>−119.20</td>
<td>2,015</td>
<td>1,379</td>
<td>644</td>
<td>8.6</td>
<td>ENF</td>
<td>2009–2015</td>
</tr>
<tr>
<td>Niwot Ridge</td>
<td>US-NR1</td>
<td>40.03</td>
<td>−105.55</td>
<td>3,050</td>
<td>873</td>
<td>629</td>
<td>1.5</td>
<td>ENF</td>
<td>2000–2014</td>
</tr>
<tr>
<td>GLEES</td>
<td>US-GLE</td>
<td>41.36</td>
<td>−106.24</td>
<td>3,190</td>
<td>1,282</td>
<td>514</td>
<td>−0.9</td>
<td>ENF</td>
<td>2001–2015</td>
</tr>
<tr>
<td>James Reserve</td>
<td>US-SCf</td>
<td>33.81</td>
<td>−116.77</td>
<td>1,770</td>
<td>637</td>
<td>626</td>
<td>12.6</td>
<td>MF</td>
<td>2007–2014</td>
</tr>
<tr>
<td>Reynolds Mountain East Aspen</td>
<td>RMEA</td>
<td>43.07</td>
<td>−116.76</td>
<td>2,055</td>
<td>987</td>
<td>599</td>
<td>5.7</td>
<td>WSA</td>
<td>2008–2012</td>
</tr>
<tr>
<td>Tonzi Ranch</td>
<td>US-Ton</td>
<td>38.43</td>
<td>−121.00</td>
<td>169</td>
<td>578</td>
<td>539</td>
<td>16.3</td>
<td>WSA</td>
<td>2002–2015</td>
</tr>
<tr>
<td>San Joaquin Experimental Range</td>
<td>US-CZ1</td>
<td>37.11</td>
<td>−119.73</td>
<td>405</td>
<td>502</td>
<td>378</td>
<td>17.7</td>
<td>WSA</td>
<td>2011–2015</td>
</tr>
<tr>
<td>Santa Rita Mesquite</td>
<td>US-SRM</td>
<td>31.82</td>
<td>−110.87</td>
<td>1,116</td>
<td>406</td>
<td>342</td>
<td>18.6</td>
<td>WSA</td>
<td>2005–2015</td>
</tr>
<tr>
<td>Vaira Ranch</td>
<td>US-Var</td>
<td>38.41</td>
<td>−120.95</td>
<td>129</td>
<td>579</td>
<td>340</td>
<td>15.8</td>
<td>GRA</td>
<td>2002–2015</td>
</tr>
<tr>
<td>Grassland</td>
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<td>33.74</td>
<td>−117.70</td>
<td>470</td>
<td>363</td>
<td>305</td>
<td>16.7</td>
<td>GRA</td>
<td>2007–2015</td>
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<tr>
<td>Walnut Gulch Kendall Grassland</td>
<td>US-Wkg</td>
<td>31.74</td>
<td>−109.94</td>
<td>1,531</td>
<td>329</td>
<td>293</td>
<td>17.0</td>
<td>GRA</td>
<td>2005–2015</td>
</tr>
<tr>
<td>Upper Sheep Aspen</td>
<td>USA</td>
<td>43.12</td>
<td>−116.72</td>
<td>1,984</td>
<td>576</td>
<td>538</td>
<td>5.9</td>
<td>OSH</td>
<td>2005–2012</td>
</tr>
<tr>
<td>Upper Sheep Sagebrush</td>
<td>USS</td>
<td>43.12</td>
<td>−116.72</td>
<td>1,878</td>
<td>575</td>
<td>500</td>
<td>6.3</td>
<td>OSH</td>
<td>2006–2012</td>
</tr>
<tr>
<td>Reynolds Mountain East Sagebrush</td>
<td>RMES</td>
<td>43.07</td>
<td>−116.76</td>
<td>2,098</td>
<td>814</td>
<td>472</td>
<td>5.3</td>
<td>OSH</td>
<td>2003–2007</td>
</tr>
</tbody>
</table>

(Continues)
2.2 Data

Sites having at least 5 years of continuous data were compiled through direct correspondence with principal investigators and/or the Ameriflux website (http://ameriflux.lbl.gov/), providing 25 flux tower sites and 223 site years of data. Data gaps due to power outages, sensor malfunctions, or low-turbulence periods were filled using multiple steps (Aubinet, Vesala, & Papale, 2012). First, night-time friction–velocity thresholds were calculated and night-time values below the threshold removed (Gu et al., 2005). Second, linear regression with the carbon dioxide flux, photosynthetically active radiation and temperature, and multiple linear regression with any combination of the three variables were removed (Gu et al., 2005). Second, linear regression with the carbon dioxide flux, photosynthetically active radiation and temperature, and multiple linear regression with any combination of the three variables were removed (Gu et al., 2005).

Third, small gaps in the 30 min data were filled using linear interpolation. Fourth, the remaining gaps in the 30 min data were filled using the relationship developed to determine the $r^2$ threshold if above 0.4, otherwise by linear interpolation. Fifth, the gap-filled 30 min data were summed to daily values and the energy balance closed by linear regression of turbulent fluxes (latent and sensible heat) and available energy ($R_{net}$ – G) forced through the origin (Goulden et al., 2012; Twine et al., 2000). Energy balance closure was not performed on sites either being cited as unnecessary (Scott, Hamerlynck, Jenerette, Moran, & Barron-Gafford, 2010) or in warm deserts, as this has shown to overestimate evapotranspiration by up to 20%, resulting in mean evapotranspiration greater than precipitation (Biederman et al., 2018). If the ground heat flux was missing from the dataset, it was estimated as

$$G = 0.35 \left( R_{net} e^{0.9 |\ln(1-fc)|} \right),$$

where $G$ is the soil heat flux, $R_{net}$ is the net radiation measured from the flux tower, and $fc$ is the fractional canopy cover (Norman, Kustas, & Humes, 1996). This step was only needed for three sites, and fractional canopy cover values were obtained from literature and discussion with flux tower principal investigators. Here, 0.36 was used for US-Vcp (Broxton et al., 2015; Harpold et al., 2015), 0.67 was used for US-Vcp, and 0.05 was used for US-Scd. Daily evapotranspiration values were limited to be a maximum of vegetation-corrected Hamon potential evapotranspiration (PET) (Rao, Sun, Ford, & Vose, 2011).

Locally measured precipitation data were used where available. Precipitation data were obtained through literature review and direct discussion with flux tower principal investigators (Table 2). Site-corrected monthly PRISM precipitation data were used to extend all precipitation datasets back to 1981. This provided a minimum 35-year distribution for multiyear dry-period detection. 800-m PRISM data were corrected to the site observations on a monthly timestep by linear regression through the origin. All site data agreed well with PRISM ($r^2 = 0.77$).

Thirty-minute flux tower measurements of temperature were aggregated to daily average values, and data gaps filled with 800-m PRISM data. Monthly aggregated temperature data were used to estimate vegetation-corrected Hamon PET (Rao et al., 2011). These data were used to identify energy-limited sites in a Budyko framework.

We used three steps to determine the contribution of snowpack storage to PAWS. Ten sites were identified as receiving snow based on monthly mean daily temperature ≤1°C (Marks, Wnistr, Reba, Pomeroy, & Kumar, 2013). At one site it was determined that snow was intermittent and that melt was fast relative to our monthly time step. Snow accumulation and melt for the other nine sites with a possible seasonal snow influence were estimated from colocated SNOTEL stations or other on-site measurements (Table 2). For three sites with snow depth but not snow water equivalent (SWE) data, precipitation was assumed to be all snow during the periods when depth was increasing, and snowmelt was assumed to be proportional to decreases in snow depth, neglecting snow compaction. SWE data were blended with rain gauge precipitation data to calculate winter snow accumulation and melt. All snowmelt was assumed to contribute to subsurface PAWS, and precipitation during snowmelt periods was assumed to be rain.

2.3 Analysis

Sites with a vegetation-corrected Hamon PET to precipitation ratio of <0.8 were considered extremely energy limited. Sites with a ratio approximately equal to one (0.8–1.2) were classified into energy...
versus moisture limited based on the slope of the regression between growing season temperature (April–September) and annual evapotranspiration, with a positive slope indicating an energy limitation (Garcia et al., 2014; Karnieli et al., 2010). This step was taken to minimize uncertainty in the vegetation-corrected Hamon PET.

A site’s mean wet-year evapotranspiration was calculated from the evapotranspiration observed during years with above-average precipitation. These values were used to detect the response of evapotranspiration to multiyear dry periods. The critical month during that year was then identified as the inflection point of the cumulative-annual evapotranspiration curve. The inflection was detected using a 3-month sliding window to minimize false detection from an anomaly or interannual monthly variability. Critical drawdown was calculated as the net drawdown of PAWS from the onset of the multiyear dry period to the critical month. Dry-period drawdown was estimated as the net drawdown of PAWS over the entire multiyear period.

The effect of the delayed contribution of snowmelt to the amount of dry-season PAWS needed to supplement evapotranspiration was assessed considering all precipitation falling as rain.

### 2.4 Sources of uncertainty

We identified four potential sources of uncertainty. First, evapotranspiration measurements are made at only a limited number of sites and do not represent all of the climate, topography, geology, and vegetation variability of this region. Further, the mean available flux tower...
record for the 25 sites was less than 9 years, and of the 223 site years of data, 58 involved multiyear dry periods.

Second, data processing to fill gaps involved assumptions, such as the decision to force close the energy balance. Literature on this topic is controversial, with some circumstantial evidence that the imbalance in the energy budget \((R_{\text{net}} - G = LE + H)\), where \(R_{\text{net}}\) is net radiation, \(G\) is the soil heat flux, \(LE\) is latent heat, and \(H\) is sensible heat, is related to an underestimation of \(LE\) and \(H\) (Wilson et al., 2002), and other analyses show that correcting for this imbalance leads to an overestimation of evapotranspiration (Biederman et al., 2018). We determined whether or not to close the energy balance based on literature reports that forced closure is especially problematic at warm desert sites (Biederman et al., 2018; Scott, 2010).

Third, our assumption that all precipitation infiltrates and contributes to PAWS could lead to an underestimation of evapotranspiration withdrawal from storage and thus PAWS at sites where high-intensity rainfall results in overland flow.

Fourth, our assumption of negligible lateral flow could lead to an overestimation of critical PAWS drawdown for sites with water convergence and an underestimation for sites with divergence (Fellows & Goulden, 2016).

3 | RESULTS

3.1 | Seasonal variability and dependence on PAWS

Mean monthly evapotranspiration and precipitation show seasonal patterns for each site, with winter periods when precipitation exceeds evapotranspiration and summer when evapotranspiration is supported by subsurface PAWS drawdown (Figure 2). Nine of the 25 sites had appreciable snowfall and snowmelt, and the remaining sites received little or no snow. The snowpack at five was sufficiently long-lasting to introduce a 1-month lag before evapotranspiration relied on subsurface PAWS (US-CZ3, US-NR1, US-Vcm, US-GLE, RMEA). The hatched areas represent evapotranspiration from sublimation (Molotch et al., 2009; Schlaepfer et al., 2014).

Evapotranspiration peaks during the winter and spring at the warmer sites and later at the colder sites. Sites with a Mediterranean climate (indicated by bold lettering in Figure 2) receive precipitation mainly during the cool season. The seven sites in the interior Southwest receive a summer monsoon (indicated by non-bold lettering in Figure 2) and have year-round precipitation. Evapotranspiration peaks during the summer at the monsoon-influenced sites, with smaller peaks in the winter at warmer sites and spring at colder sites. Evapotranspiration peaks in the summer at the Colorado and Wyoming sites. PET values are shown in Figure 2 for reference.

Annual evapotranspiration averaged 514–892 mm yr\(^{-1}\) at the evergreen needleleaf and mixed forest sites and 131–502 mm yr\(^{-1}\) at the savanna, grassland, and shrubland sites in Arizona and southern California. Annual evapotranspiration from subsurface storage were calculated by integrating the shaded areas in Figure 2 for each site year (Figure S1). The four forested sites in California had the greatest values, averaging about 258–512 mm yr\(^{-1}\), and savanna, grassland, and shrubland sites in Arizona and southern California had the least, 67–198 mm yr\(^{-1}\) (Figure 3). Over half of the annual evapotranspiration at most of the Mediterranean climate sites was supported by subsurface storage (52 ± 8%, mean ± standard deviation) versus less than one-third at the monsoon-dominated sites (31 ± 9%).

Shrublands showed the largest intersite range of mean evapotranspiration, 131–538 mm yr\(^{-1}\), and large within-site interannual ranges; for example, 0.45–1.73 times the mean at US-SCd in southern California (Table 1; Figure 4). However, the three Idaho shrublands, which are energy limited, had ranges averaging 0.95–1.04 times the mean. Evergreen needleleaf forests also exhibited a large range between sites, with mean evapotranspiration values ranging from 514 to 892 mm yr\(^{-1}\). Within-site interannual ranges were relatively low for US-NR1 (0.93–1.07) and US-CZ3 (0.92–1.12), with the first energy limited and the second non-energy limited. The range for the mixed-forest US-CZ2 was much wider (0.70–1.40). The two relatively warm forested sites in New Mexico had asymmetric ranges (0.49–1.21). Savanna and grassland sites averaged 342–599 and 293–340 mm yr\(^{-1}\), respectively; and had interannual ranges from 0.67–1.54 at US-Wkg and 0.74–1.50 at US-CZ1 to 0.94–1.05 at energy-limited RMEA.

3.2 | Maximum evapotranspiration by land cover type

Annual evapotranspiration increased with precipitation up to a maximum threshold that varied by land cover type (Figure 4a). Two evergreen needleleaf forest (US-GLE and US-NR1), one woody savanna (RMEA), and three shrubland (RMES, USA, USS) sites were energy limited. Removing these energy-limited sites and years with below-average precipitation gives mean values of maximum water year evapotranspiration of 833, 861, 558, 367, and 254 mm yr\(^{-1}\) for the evergreen needleleaf forest, mixed forest, woody savanna, grassland, and shrubland land cover types, respectively (Figure 4b–c). This is equivalent to 84, 110, 113, 87, and 95% of mean non-energy-limited site precipitation, respectively.

3.3 | Site response to multiyear dry periods

High evaporative index values across many sites and years suggest that PAWS helps to support evapotranspiration during multiyear dry periods (Figure 5). Thirteen of the sites had at least one multiyear dry period in the record, and two of the sites had two dry periods (Table 3). All but two of these (US-CZ3 and US-Blo) showed an attenuation of evapotranspiration (Figure 6). The two evergreen needleleaf forest sites failed to show a cumulative decrease in storage and neither experienced an attenuation of evapotranspiration. The two mixed-forest sites had critical PAWS drawdowns of 334 and 293 mm and resistances of 21 months. All woody savanna sites exhibited an attenuation of evapotranspiration, with one, US-SRM, showing no cumulative depletion of storage. US-CZ1 and US-SRM had low resistances, 8 and 12 months, respectively, compared with US-Ton, which had two multiyear dry periods, both of which showed resistances of 20 months before an attenuation of evapotranspiration was observed. All grassland multiyear dry periods exhibited an attenuation of evapotranspiration, with one site having two dry periods but no PAWS drawdown.
US-Var) and the other (US-SCg) having a critical PAWS drawdown of 40 mm. Dry-period resistance for grasslands ranged from 8 to 32 months. All shrubland sites experiencing a multiyear dry period showed an attenuation of evapotranspiration, with only US-SCc showing no cumulative depletion of PAWS. Shrubland critical PAWS drawdown ranged from 38 to 288 mm, with resistances ranging from 11 to 23 months. All land cover types showed continued drawdown of PAWS through the remainder of their multiyear dry periods.

3.4 | Effect of snowpack on PAWS dependency

Precipitation that falls as snow rather than rain delays infiltration, which shortens the duration of dry season drawdown and reduces the amount of mean annual evapotranspiration supported by PAWS. The occurrence of snow rather than rain, and the timing of subsequent melt, augmented subsurface PAWS by an average of about 4% at US-Vcp, 4% at US-CZ3, 17% at US-NR1, 20% at US-GLE, 9% at RMEA, and near zero or negative at US-Vcm, USA, USS, and RMES (Figure S2). The contribution of snowmelt during peak evapotranspiration years was as high as 8% at US-Vcp, 10% at US-CZ3, 7% at US-NR1, 23% at US-GLE, and 4% at RMEA.

4 | DISCUSSION

4.1 | Annual and seasonal evapotranspiration by land cover type and climate

Annual evapotranspiration measured across the 25 sites ranged from 66 to 1,066 mm yr⁻¹, with higher rates in evergreen-needleleaf and mixed forests and lower rates in grasslands and shrublands in Arizona and southern California. Evapotranspiration was positively correlated with precipitation ($r^2 = 0.58$) and negatively with temperature.
FIGURE 3  Amount of evapotranspiration (ET) supported by plant-accessible water storage for each water year on record by site. Site abbreviation is followed by state abbreviation. Other site characteristics are given in Table 1. Vertical black lines separate land cover types. Bold denotes Mediterranean climate sites.

FIGURE 4  (a.1–a.5) Annual precipitation versus evapotranspiration (ET) by land cover type for all sites (b.1–b.5 legend included here), (b.1–b.5) annual precipitation versus evapotranspiration after removing all energy- and precipitation-limited sites and site years with annual precipitation below the mean, and (c.1–c.5) show ranges of maximum ET for the five land cover types.
and cooler, wetter sites typically had a higher annual evapotranspiration (Figure S3).

We further investigated the relationship between evapotranspiration, temperature, and precipitation seasonality by classifying the sites into four groups: energy-limited Mediterranean (Idaho), non-energy-limited Mediterranean (California), energy-limited monsoon (Wyoming and Colorado), and non-energy-limited monsoon (New Mexico and Arizona). Shrublands showed the greatest variation between energy-limited and non-energy-limited sites, with energy-limited Mediterranean locations exhibiting the highest average annual evapotranspiration (509 mm) and non-energy-limited Mediterranean sites exhibiting the lowest (194 mm). Shrublands displayed the greatest relative ranges in annual evapotranspiration and precipitation and have been shown to have high variability in leaf area index and spacing as a function of water availability, shrub size, species, and competition (Phillips & MacMahon, 1981). A relatively high vegetation density at the energy-limited Mediterranean sites, which also have higher annual precipitation, may have offset a shorter growing season. No significant correlations in annual evapotranspiration with climate were apparent at the remaining sites. One site, US-Vcp, showed a mean annual evapotranspiration that was greater than mean annual precipitation. Calculations of the Topographic Wetness Index (not shown) indicated that US-Vcp is in an area of water convergence, suggesting that evapotranspiration may be supported by lateral inputs.

Mediterranean sites showed distinct peaks in evapotranspiration during summer, when precipitation was generally low. Evapotranspiration at sites experiencing a monsoon generally peaked with summer precipitation. Most sites having significant snow accumulation showed evapotranspiration peaking 3–5 months following the last significant winter storm. The consistent lag of peak evapotranspiration after the transition from snow accumulation to melt suggests that an earlier timing of peak snow water equivalent may lead to earlier peaks in evapotranspiration, consistent with the findings of Hamlet, Mote, Clark, & Lettenmaier (2007).

4.2 Dry-season water drawdown

Figures 2, 3, 5 show that evapotranspiration in all land cover types and climates is sustained in part by the seasonal withdrawal of subsurface storage. The fraction of mean annual evapotranspiration supported by seasonal subsurface PAWS drawdown ranged from 16 to 64%. PAWS drawdown had a weak positive correlation with precipitation \( r^2 = 0.10, p = 0.005 \) and a strong positive correlation with annual temperature \( r^2 = 0.70, p < 0.001 \) at sites with seasonal snowpack (Figure S4). Drawdown at rain-dominated sites was positively correlated with precipitation \( r^2 = 0.51, p < 0.001 \) and negatively with temperature \( r^2 = 0.49, p < 0.001 \). This indicates the lagged contribution of snowmelt to PAWS currently reduces the dependence on dry-season PAWS and suggests these areas may be vulnerable to an increased reliance on seasonal PAWS with climate warming.

Evapotranspiration at sites with a Mediterranean climate showed the most dependency on subsurface PAWS, with average values of 53% for non-energy-limited and 48% for energy-limited sites. Monsoon-influenced sites depended on PAWS for 33% of annual evapotranspiration at non-energy-limited and 18% at energy-limited sites. This is consistent with the seasonal trends of evapotranspiration in Figure 2, which show the peak growing season for Mediterranean sites occurring during a period with little to no rain, whereas evapotranspiration at monsoon sites peaks with monsoonal precipitation.
temperatures shift precipitation from snow to rain and melt snow. For example, as warmer temperatures shift precipitation from snow to rain and melt snow earlier, the “rain + snow” lines on Figure 3 will more closely resemble the “precipitation” lines, increasing the shaded areas that represent evapotranspiration from PAWS drawdown. At warmer snow sites such as US-Vcp, US-Vcm, and US-CZ3, this effect will be relatively small in most years but important in years when late-spring (April–June) precipitation is small (Figure S1). Colder sites that currently have lower dependence on PAWS, such as US-NR1 and US-GLE, appear the most susceptible to increases in PAWS demand with a shift from snow to rain (Figure S1).

Loss of snowpack storage had little or no effect on reliance on PAWS at the energy-limited woody savanna and shrubland sites (RMEA, USA, USS, and RMES) in most years, but appear sensitive to precipitation type in years with little spring rain or snowfall. The US-CZ2 and US-SCf sites relied heavily on year-over-year PAWS drawdown during multiyear dry periods and are also particularly vulnerable to episodic tree mortality (Bales et al., 2018). A loss of snowpack storage with warming at some sites may increase the reliance on PAWS drawdown with implications for forest die-off. As warming extends the growing season, higher spring evapotranspiration at most sites will increase withdrawal from PAWS (Figures 3 and S1). In general, the effect will be more pronounced at sites that currently have significant snow accumulation, limited dependence on PAWS, and relatively uniform monthly precipitation (e.g. US-NR1, US-GLE). At all sites that currently have snowpack storage, the combination of higher evapotranspiration in a warmer spring and limited late-spring and early summer precipitation will increase dependence on PAWS. That is, as snow shifts to rain, the timing of precipitation will become more important in determining PAWS drawdown and thus moisture stress. Although large winter snow accumulation can somewhat offset a drier spring, interannual variability in spring temperature and energy balance, and thus snowmelt timing, will also become more important.

### 4.3 Evapotranspiration supported by PAWS during multi-dry year periods

Evergreen needleleaf forests maintained high rates of evapotranspiration despite the occurrence of multiyear dry periods, whereas evapotranspiration in the other land cover types was attenuated (Table 3). Figure 2 shows that measured evapotranspiration closely tracked evaporative demand, with a narrow gap for sites where annual precipitation grossly exceeded evapotranspiration (US-Blo and US-CZ3). A smaller gap between measured and potential evapotranspiration was observed at energy-limited sites (US-NR1 and US-GLE). This suggests evergreen needleleaf forests occur at locations with sufficient access to water to meet the evaporative demand. Mixed-forest sites used substantial amounts of subsurface PAWS, and the remaining land cover types varied significantly, ranging from no dry-period drawdown to several hundred millimetres. High values of net drawdown at mixed forested sites suggests that current levels of evapotranspiration may be unsustainable, with drought-induced tree mortality observed at US-CZ2 during California’s 2012–2015 drought (Bales et al., 2018).
5 | CONCLUSIONS

We used a suite of eddy covariance flux towers across the semiarid western United States to assess the response of evapotranspiration to multiyear dry periods. Mediterranean climate sites showed greater dependency on seasonal plant-accessible water storage (PAWS), suggesting that vegetation distribution in these areas is particularly sensitive to subsurface PAWS capacity. Time series during multiyear dry periods showed that all land cover types except evergreen needleleaf forests exhibited a year-over-year depletion of subsurface PAWS, which allowed a normal range of evapotranspiration to be maintained. Evergreen needleleaf forests maintained wet-year evapotranspiration rates with no net PAWS drawdown despite multiyear dry periods, indicating sufficient available water to meet the evapotranspiration demand. Mixed forests withdrew the most from PAWS, with one site drawing more than 530 mm over a multiyear dry period. The delayed recharge of PAWS by snowmelt most benefits the energy-limited evergreen needleleaf forests, where it decreases seasonal drawdown by 17–20%. A shift from snow to rain may increase the vulnerability of forests to multiyear dry periods.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.