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Spatially distributed water-balance and meteorological data from the rain-snow transition, southern Sierra Nevada, California

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Abstract

We strategically placed spatially distributed sensors to provide representative measures of changes in snowpack and subsurface water storage, plus the fluxes affecting these stores, in a set of nested headwater catchments. We present eight years of hourly snow-depth, soil-moisture and soil-temperature data, and 14 years of quarter-hourly streamflow and meteorological data that detail water-balance processes at the rain-snow transition at Providence Creek in the southern Sierra Nevada, California. Providence Creek is the co-operated long-term study run by the Southern Sierra Critical Zone Observatory and the U.S.D.A. Forest Service Pacific Southwest Research Station's Kings River Experimental Watersheds. The 4-km^2 montane Providence Creek catchment spans the current rain-snow transition elevation of 1500–2100 m. Two meteorological stations bracket the high and low elevations of the catchment, measuring air temperature, relative humidity, solar radiation, precipitation, wind speed and direction, and snow depth, and at the higher station, snow water equivalent. Paired flumes at three subcatchments and a V-notch weir at the integrating catchment measure quarter-hourly streamflow. Measurements of meteorological and streamflow data began in 2002. Between 2008 and 2010, 50 sensor nodes were added to measure distributed snow depth, air temperature, soil temperature and soil moisture down to a depth of 1 m below the surface. These sensor nodes were installed to capture the lateral differences of aspect and canopy coverage. Data are available at hourly and daily intervals by water year (October 1- September 30) in non-proprietary formats from online data repositories. Data for the Southern Sierra Critical Zone Observatory distributed snow and soil datasets are at https://doi.org/10.6071/Z7WC73. Kings River Experimental Watersheds stream-discharge data are available from https://doi.org/10.2737/RDS-2017-0037.

1 Introduction

Snowpack and subsurface water storage in the Sierra Nevada support ecosystem health and downstream water supply, along with recreational and aesthetic value, and other water-related services (SNEP, 1996). Two major challenges threatening these

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benefits are the effects of long-term forest-fire suppression and the effects of climate change. Overstocked montane coniferous forests, the result of a century of fire suppression in this region, are more prone to high-intensity wildfire, and less resilient in the face of droughts. Climate change will stress the balance between precipitation, subsurface water storage, and evapotranspiration, as precipitation shifts from snow to rain, and atmospheric water demand increases through longer and warmer growing seasons (Bales et al., 2018). During the 2012–15 California drought, Sierra Nevada forests experienced extensive mortality due in part to water stress and subsequent insect and fungal pathogens.

Thinning of overgrown forests can both lower the risk of high-intensity wildfire and lower forest drought stress (Stephens et al., 2012). Prior to 2002, there was little information on the hydrologic impacts of these treatments. The Kings River Experimental Watersheds (KREW) project began in part to answer these questions. Three subcatchments in Providence Creek, and a nearby one draining to Duff Creek, were assigned treatments, including mechanical thinning, prescribed burning, a combination of mechanical thinning and prescribed burning, and a control. Nearly ten years of pre-treatment data act as an additional control. At Providence, mechanical thinning was completed 2011–2012, and prescribed burning occurred in 2015 and 2016.

Another need for the water-measurement system was the lack of information on snow depth and soil-moisture variability across the landscape, on sub-daily timescales. For example, historical records of snowpack at a few select locations, useful as a baseline index, only capture a fraction of the variation in snow depth and snow water equivalent across the mountains (Kerkez et al. 2011, Oroza 2017). Those historical measurement approaches prove inadequate to support sound decision making in a populous, semi-arid state under a changing climate (Cantor et al. 2018). Distributed sensor nodes that are stratified by elevation, canopy coverage, and aspect can better describe temporal and spatial patterns in the water balance needed by a new generation of forecast tools (Zheng et al. 2016). The Southern Sierra Critical Zone Observatory (SSCZO) began in 2007 to quantify these measurements through distributed sensor nodes that are stratified by elevation, canopy coverage, and aspect. The SSCZO is also a testbed for improving the communication and efficacy of spatial-measurement networks (Kerkez et al., 2011; Oroza et al., 2018).

We present hydrometeorological variables in the 14-year KREW dataset for streamflow, snow depth, snow density, air temperature, relative humidity, precipitation, and wind speed and direction. These serve as a basis for additional work in the catchments on sediment, soil and stream chemistry, vegetation composition, and the impacts of treatments. We also present hydrometeorological variables in an eight-year SSCZO dataset for snow depth, soil moisture and temperature, and air temperature and humidity distributed across the landscape.

The Providence Creek catchment is one part of two larger studies. First, KREW established and maintains nested headwater catchments at Providence plus the snow-dominated Bull Creek catchments, and a catchment in the adjacent Teakettle Experimental Forest, for assessing the impacts of forest-management treatments on headwater soils and catchment outputs (Hunsaker et al., 2012). Second, the SSCZO program established four focal measurement sites along an elevation transect extending over 400–2700 m elevation (Goulden et al., 2012), of which Providence is one site. Major SSCZO research questions focus on the links between climate, regolith properties, vegetation, biogeochemistry, hydrology and the response

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Manuscript under review for journal Earth Syst. Sci. Data
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of the mountain ecosystem and catchments to disturbance and climate change. Related studies include evaluation of the transect of eddy covariance and evapotranspiration (Goulden et al., 2012, Goulden and Bales 2014, Saksa et al., 2017, Bales et al., 2018); soil moisture (Oroza et al., 2018), hydrologic modeling (Tague and Peng, 2013, Bart et al., 2016, Son et al., 2016, Bart and Tague, 2017; Jepsen et al., 2016), biochemical studies (Liu et al., 2012, Carey et al., 2016, Aciego et al., 2017, Arvin et al., 2017, Hunsaker and Johnson, 2017); geophysical research (Hahm et al., 2014, Holbrook et al., 2014), and sediment composition (Stacy et al., 2015, McCorkle et al., 2016). Regolith water storage is further described in Klos et al. (2018).

2 Site description

The Providence site is located approximately 40 miles northeast of Fresno, California, in the Sierra National Forest. The 4.6 km^2 catchment (P300) is predominantly southwest aspect, with a moderate slope (19–22%) and elevations of 1700–2100 m (Table 1). Instruments are installed in three subcatchments (P301, P303, P304; Fig. 1). The site has a Mediterranean climate, with cool, wet winters and dry summers that last from approximately May through October. Precipitation falls as a mix of rain and snow, and precipitation transitions from majority rainfall to majority snow typically about 2000 m in elevation (Bales et al., 2011; Safeeq and Hunsaker, 2016).

The catchments are underlain by Dinkey Creek Granodiorite and Bald Mountain Leucogranite (Bateman 1992). Soil is dominated by the Shaver, Cagwin, and Gerle series (Johnson et al. 2010). Land cover is dominated by mature mixed-conifer forest, but there are also areas of exposed bedrock and small meadow systems. Primary vegetation is Sierra mixed-conifer forest, with white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyii*), incense-cedar (*Calocedrus decurrens*), and California black oak (*Quercus kelloggii*; Dolanc and Hunsaker, 2017).

3 Meteorological data

Meteorological stations were installed at 1975 (Upper Met) and 1750 m (Lower Met) elevations in the Providence catchment in 2002–2003 (Table 3). Precipitation is measured with a Belfort 5-780 shielded weighing rain gauge (Belfort Instrument, Baltimore, MD, USA); the instrument is mounted 3 m above the ground. A Met One 013 wind-speed sensor and 023 wind-direction sensor (Met One, Grants Pass, OR, USA), a Vaisala HMP45C relative-humidity and air-temperature sensor (Vaisala Corporation, Helsinki, Finland), a Kipp and Zonen CM3 pyranometer (Kipp and Zonen B.V., Delft, The Netherlands), and Judd acoustic depth sensor (Judd Communications LLC, Salt Lake City, UT, USA) are mounted on a 6 m tower at the site. Snow water equivalent is measured at the Upper Met with a WaterSaver 3 m snow pillow (Snowsaver, Commerce City, CO, USA) with a Sensotec Pressure Tranducer (Honeywell Inc., Columbus, OH, USA) installed

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approximately 4 m to the north of the weather tower. Data are recorded at each station with a Campbell CR10x (Campbell Inc., Logan, UT, USA) at 15 minute intervals.

Manual measurements for instrument verification were made at twice-monthly visits unless delayed by weather. Precipitation at the weighing gauge was verified against measurement records from the snow pillow and nearby weather stations (Table 2; further information about precipitation data assurance in Safeeq and Hunsaker, 2016).

4 Distributed-sensor clusters

4.1 Upper and Lower Met

Snow depth, soil moisture and soil temperature are measured at 27 sensor nodes around the Upper Met and Lower Met (Bales et al., 2011; Table 3). Distance to snow/soil surface is measured in the open, at the drip edge and under canopies with an acoustic depth sensor (Judd Communications LLC, Salt Lake City, UT, USA). Global solar radiation is measured using a Li-Cor PY-200 pyranometer (Li-COR Inc., Lincoln, NE, USA). Soil volumetric water content and soil temperature are measured using ECHO-TM sensors (METER Group, Pullman, WA, USA) at depths of 10, 30, 60, and 90 cm below the mineral-soil surface under each snow-depth sensor. Matric potential is measured at the same depths with an MPS-1 sensor (METER Group, Pullman, WA, USA).

Instrument nodes are sited in clusters at lower Providence South-facing (LowMetS) and North-facing (LowMetN), Upper Providence South-facing (UpMetS), North-facing (UpMetN) and Flat aspect (UpMetF). At each cluster, 5–7 sensor nodes were installed according to tree species and canopy coverage (drip-edge, under canopy, open canopy) in 2008. Data storage and sensor control are conducted at each of the five sites with a Campbell Scientific CR1000 datalogger and an AM16/32B multiplexer (Campbell Scientific, Inc., Logan, UT, USA). Data are recorded at 10 minute intervals, with 30 minute averages reported.

4.2 P301 sensor network

In summer 2009, 23 nodes in the P301 subcatchment were instrumented with sensors to measure snow depth, air temperature, relative humidity, and soil moisture, temperature and matric potential (Fig. 2; Table 3). The same sensors are used here as in the Upper and Lower Met clusters (section 4.1). Air temperature and relative humidity are measured with a Sensirion SHT15 (Sensirion AG Switzerland, Stafa, Switzerland). Nodes are sited to capture differences in aspect (north vs. south), meadow structure (open meadow, a narrow meadow channel, transition to forest outside of meadow), and canopy coverage. Data are collected at individual nodes with Metronome Neomote dataloggers (Metronome Systems LLC., Berkeley, CA, USA) with custom sensor wiring board at 15 minute intervals. These P301 sensor network data are available beginning in WY 2010 (October 1, 2009). This installation has been the test site for two generations of wireless networking (Kerkez et al., 2011; Oroza et al., 2016; Oroza et al., 2018).

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-69
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 8 June 2018

5 Streamflow

Stream-discharge monitoring began in 2004 at subcatchments P301, P303, and P304 and in 2006 at integrating catchment P300. Subcatchment discharge is quantified with one large (61 cm for P301 and P303; 30.5 cm for P304) and one small (7.6 cm) fiberglass Montana flume (Tracom Inc., Alpharetta, GA, USA or Engineering Flow Products, Tempe, AZ, USA) to capture the range of flows while a 120° v-notch weir is used at P300 (Safeeq and Hunsaker, 2016). An ISCO 730 air bubbler (Teledyne Isco, Lincoln, NE, USA) is the primary stage-measurement device. Backup stage measurements were initially obtained using either an AquaRod capacitance water-level sensor (Advanced Measurements and Controls, Inc., Camano Island, WA) or a Telog pressure transducer (Trimble Water, Inc., Rochester, NY, USA). Levellogger Edge M5 pressure transducers (Solinst Inc., Georgetown, ON, Canada) were installed for backup stage measurement in water year 2011. A Barologger barometer (Solinst Inc., Georgetown, ON, Canada) records barometric pressure for atmospheric corrections to stage. Stage is converted to flow using the standard rating curve supplied by the flume manufacturer.

6 Example data

Upper and Lower Met stations receive similar amounts of precipitation but a greater percentage falls as rain at Lower Met. The elevation difference between Upper and Lower Met (225 m) leads to a deeper and more-persistent snowpack at Upper Met (Fig. 3a, 4a–d). Wet-up at the two sites occurs almost simultaneously, but soil moisture at Lower Met is higher and stays wetter later due to finer soil texture (Fig. 3, 4ac). Measurement nodes in the P301 meadow have higher soil moisture than most other points in the network, increasing variability (Figure 4e).

Stream discharge can peak early in the year during large fall storms, such as in WY 2010 and 2011 (Fig. 4g). In WY 2011, peak instantaneous flows exceeded 60 mm d^{-1} in subcatchments P303 and P300 (Fig. 5a). While these storms may cause the highest instantaneous flows, the bulk of stream discharge occurs as a result of spring snowmelt (Fig. 5b). In extremely dry years such as WY 2014 or 2015, P300, P303 and P304 remained perennial, but P301 surface flow stopped. After 1 June, soil moisture dries to lows of 10–13% (Fig. 3b, 4ace) and stream discharge is dominated by daily evapotranspiration periods (Fig. 5c).

7 Data availability

Meteorological data were processed to remove noise, assure data quality and fill gaps using nearby rain gauges (Safeeq and Hunsaker, 2016). Missing meteorological and stream discharge data are indicated by blank cells; estimates were made when possible through linear interpolation or through a regression model with a closely correlated site. Filled or estimated values are flagged in the data files. Sensor-network and stream-discharge data are available through online data repositories. Distributed snow depth, air temperature, and soil moisture and temperature are available through the California Digital Library (see Bales et al., 2017, https://doi.org/10.6071/Z7WC73). Gaps are filled through regression with a nearby sensor node, which is selected based on the best correlation. Multiple neighboring nodes may be selected if needed, and different neighboring nodes may be used to fill each measurement. Short gaps, or gaps in soil temperature, may be filled through linear interpolation. Metadata, including process notes, data headers, and data units are available from the data repositories. Data in the Upper and Lower Met sensor clusters are coded and sorted by site and aspect; naming codes for all measurement points are presented in Table 3. Stream-discharge data are available from the Forest Service Research Data Archive Repository (Hunsaker and Safeeq, 2017; https://doi.org/10.2737/RDS-2017-0037).

8 Summary

An eight to 14 year meteorological and hydrologic data record is presented for a set of nested catchments in the southern Sierra Nevada. Distributed snow depth and soil temperature and moisture combined with two meteorological stations and a long-term stream-discharge record provide a means of establishing natural variability as well as testing hydrologic process models in a productive montane forest.

Author contributions

R. Bales, M. Conklin and S. Glaser designed the sensor networks. M. Meadows, E. Stacy, X. Meng and C. Oroza installed and maintained the sensor networks and processed the sensor-network data. M. Safeeq and J. Wagenbrenner were responsible for the meteorological stations and stream gauges. E. Stacy and R. Bales prepared the manuscript, with contributions from all authors.

Competing interests

S. Glaser is a co-founder and has intellectual property associated with Metronome Systems.

Special issue statement

This article is part of the special issue “Hydrometeorological data from mountain and alpine research catchments”. It is not associated with a conference.

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Discussion started: 8 June 2018

Table 1. Characteristics of three subcatchments and the integrating P300 catchment. (Adapted from Safeeq and Hunsaker, 2016).

Site	Catchment	Drainage area, ha	Average altitude, m	Relief, m	Average aspect, degrees	Average slope, %
Providence	P301	99	1979	318	208	19
Providence	P303	132	1905	292	233	20
Providence	P304	49	1899	213	249	22
Providence	P300	461	1883	424	223	21

Table 2. Nearby stations used for verification of the precipitation data at KREW Providence meteorological stations

Site Name (code)	Operator	Web address	Elevation, m
Tamarack Summit *(TMR)*	US Bureau of Reclamation	http://cdec.water.ca.gov/selectQuery.html	2301
Huntington Lake *(HNT)*	US Bureau of Reclamation	http://cdec.water.ca.gov/selectQuery.html	2134
Wishon Dam *(WSD)*	Pacific Gas & Electric	http://cdec.water.ca.gov/selectQuery.html	1996
KREW NADP (CA28)	USFS PSW Research Station	http://nadp.sws.uiuc.edu/data/sites/siteDetails.aspx?net=NTN&id=CA28	1951

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-69
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Table 3. Measurement locations and explanation of coding

Code	Description	UTM northing[1], m	UTM easting[1], m	Elevation, m
	Stream gauges			
P300	Integrating stream gauge for Providence Creek (P301, P303, P304)	303993	4103090	1684
P301	Providence Creek stream gauge station on P301	303987	4103886	1792
P303	Providence Creek stream gauge station on P303	304571	4103274	1731
P304	Providence Creek stream gauge station on P304	304708	4102923	1768
D102	Duff Creek stream gauge station on D102	303994	4101534	1487
	Meteorological stations			
Upper Prov Met	Meteorological station	305967	4103683	1981
Lower Prov Met	Meteorological station	304197	4103392	1753
	Lower Met North - LowMetN: Snow, soil and air sensor clusters, north aspect			
Open	Open canopy sensor node	304222	4103548	1733
CDde	*Calocedrus decurrens* (incensecedar), drip edge	304228	4103562	1733
CDuc	*C. decurrens*, under canopy	304230	4103562	1733
ACde	*Abies concolor* (white fir), drip edge	304230	4103556	1732
ACuc	*A. concolor*, under canopy	304230	4103559	1732
	Lower Met South - LowMetS: Snow, soil and air sensor clusters, south aspect			
Open	Open canopy sensor node	304098	4103556	1737
PPde	*Pinus ponderosa* (ponderosa pine), drip edge	304100	4103560	1738
PPuc	*P. ponderosa*, under canopy	304101	4103559	1738
ACde	*C. decurrens*, drip edge	304102	4103551	1737
ACuc	*C. decurrens* under canopy	304103	4103549	1737
	Upper Met Flat - UpMetF: Snow, soil and air sensor clusters, flat aspect			
Open	Open canopy sensor node	305901	4103899	1983
PPde	*P. ponderosa*, drip edge	305903	4103901	1983
PPuc	*P. ponderosa*, under canopy	305904	4103901	1983
ACde	*A. concolor*, drip edge	305898	4103883	1983
ACuc	*A. concolor*, under canopy	305900	4103882	1983

Code	Description	UTM northing[1], m	UTM easting[1], m	Elevation, m
	Upper Met South - UpMetS: Snow, soil and air sensor clusters, south aspect			
Open	Open canopy sensor node	305856	4103849	1977
QKde	*Quercus kelloggii* (black oak), drip edge	305848	4103852	1977
QKuc	*Q. kelloggii*, under canopy	305843	4103853	1977
ACde	*A. concolor*, drip edge	305842	4103844	1975
ACuc	*A. concolor*, under canopy	305845	4103843	1975
	Upper Met North - UpMetN: Snow, soil and air sensor clusters, north aspect			
Open	Open canopy sensor node	305961	4103876	1975
ACde	*A. concolor*, drip edge	305940	4103868	1979
ACuc	*A. concolor*, under canopy	305941	4103868	1979
CDde, or xxCDde	*C.decurrens*, drip edge, marked xx after tree removed during thinning	305955	4103871	1977
CDuc, or xxCDuc	*C. decurrens*, under canopy, marked xx after tree removed during thinning	305958	4103867	1978
PLde	*Pinus lambertiana*, drip edge	305949	4103873	1977
PLuc	*P. lambertiana*, under canopy	305951	4103870	1978
	P301 sensor network			
CZO-1	Open canopy near CZT-1	304902	4104671	2014
CZO-2	South drip edge of CZT-1	304913	4104671	2015
CZO-3	South under canopy of CZT-1	304913	4104675	2015
CZO-4	North under canopy of CZT-1	304913	4104679	2015
CZO-5	North drip edge of CZT-1	304913	4104683	2015
CZO-6	West tree drip edge of Upper Meadow P301 Transect	304963	4104840	1994
CZO-7	Open meadow of Upper Meadow P301 Transect	304966	4104845	1993
CZO-8	East tree drip edge of Upper Meadow P301 Transect	304967	4104850	1994
CZO-9	Meadow open canopy at P301 Narrow Meadow Transect	304836	4104906	1991
CZO-10	South-facing open canopy at Narrow Meadow Transect	304841	4104941	1997
CZO-26	forest-meadow interface at Narrow Meadow Transect	304836	4104907	1991
CZO-12	South-facing *Abies concolor* under canopy at Narrow Meadow Transect	304830	4104929	1995

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-69
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 8 June 2018

Code	Description	UTM northing[1], m	UTM easting[1], m	Elevation, m
CZO-29	South-facing *A. concolor* drip edge at Narrow Meadow Transect	304827	4104929	1995
CZO-14	North-facing open canopy at P301 Cedars	304437	4104739	1970
CZO-30	North-facing *Calocedrus decurrens* drip edge at P301 Cedars	304441	4104735	1971
CZO-16	North-facing *C. decurrens* under canopy at P301 Cedars	304450	4104738	1973
CZO-17	South-facing open canopy at P301 Cedars	304422	4104780	1972
CZO-18	South-facing *A. concolor* drip edge at P301 Cedars	304426	4104773	1972
CZO-19	South-facing *A. concolor* under canopy at P301 Cedars	304431	4104774	1972
CZO-20	North-facing open canopy at P301 Lower meadow	304353	4104655	1961
CZO-21	North-facing *A. concolor* drip edge at P301 Lower meadow	304352	4104651	1961
CZO-22	North-facing *A. concolor* under canopy at P301 Lower meadow	304350	4104648	1961
CZO-25	North-facing open canopy Forest-Meadow Interface at P301 Lower meadow	304352	4104705	1960

[1]Geographic coordinates are in Universal Transverse Mercator (UTM) projection, North American 1983 Datum, Zone 11.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-69
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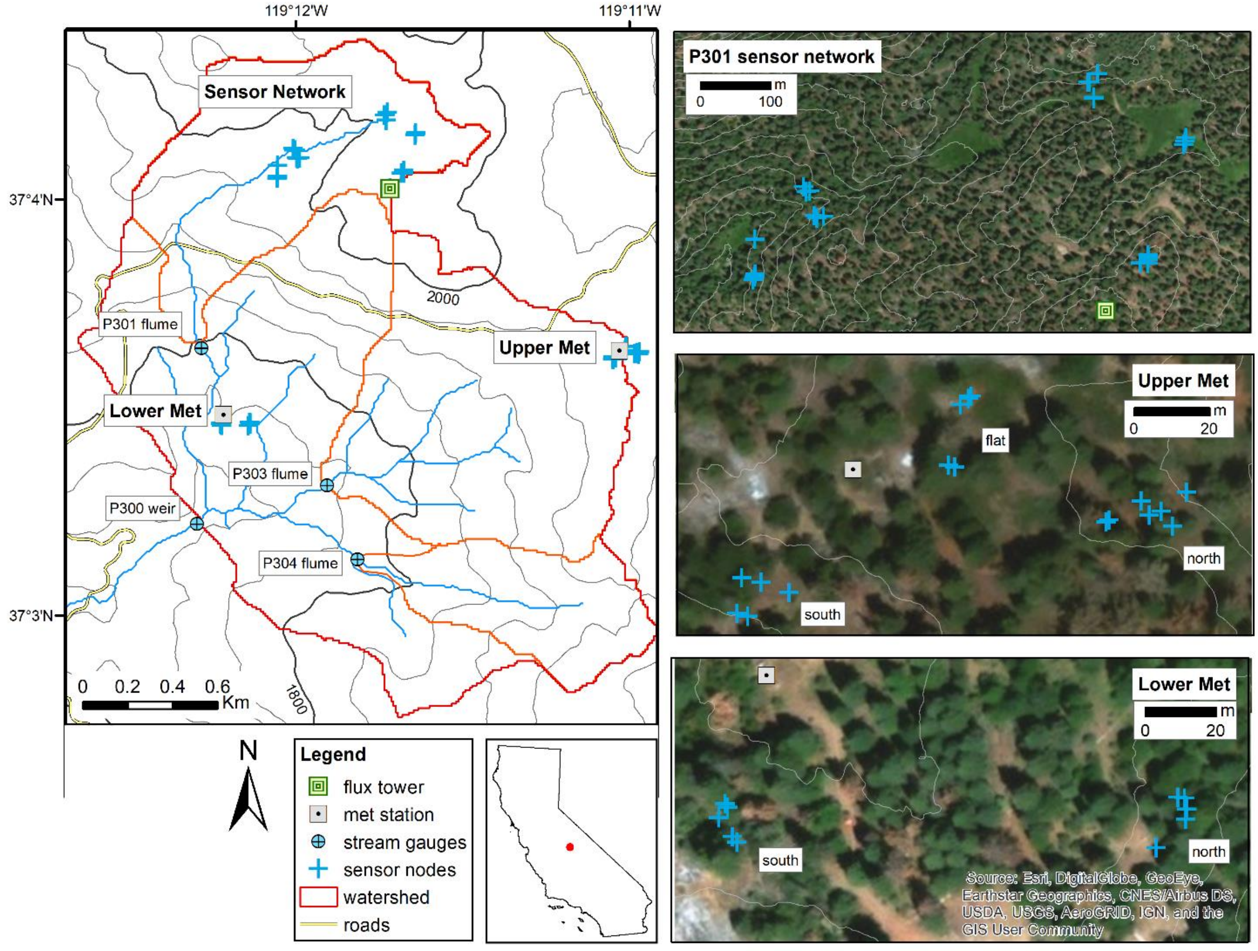

Figure 1: Map of the Providence Creek catchment, showing locations of the meteorological stations, sensor nodes, and stream-gauging stations as well as streams and catchment boundaries. Inset images show instruments and satellite imagery for the P301 network, Upper Met, and Lower Met on 9 July 2016. (Topographic data: EDNA filled DEM grid, U.S. Geological Survey, 2003. Satellite data: ESRI world imagery basemap compiled from Digital Globe and other sources).

Figure 2. Sensor nodes in the upper P301 meadow.

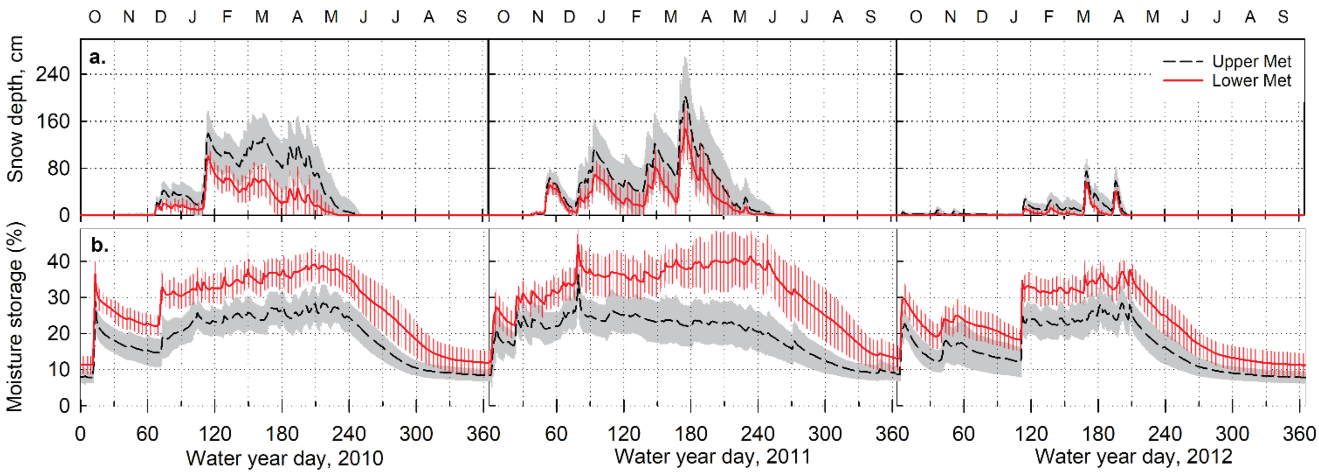

Figure 3. Measures of (a) snow depth and (b) soil water content to 1-m depth at 27 measurement nodes at Upper and Lower Met sites. Lines represent site means and shading shows ± one standard deviation.

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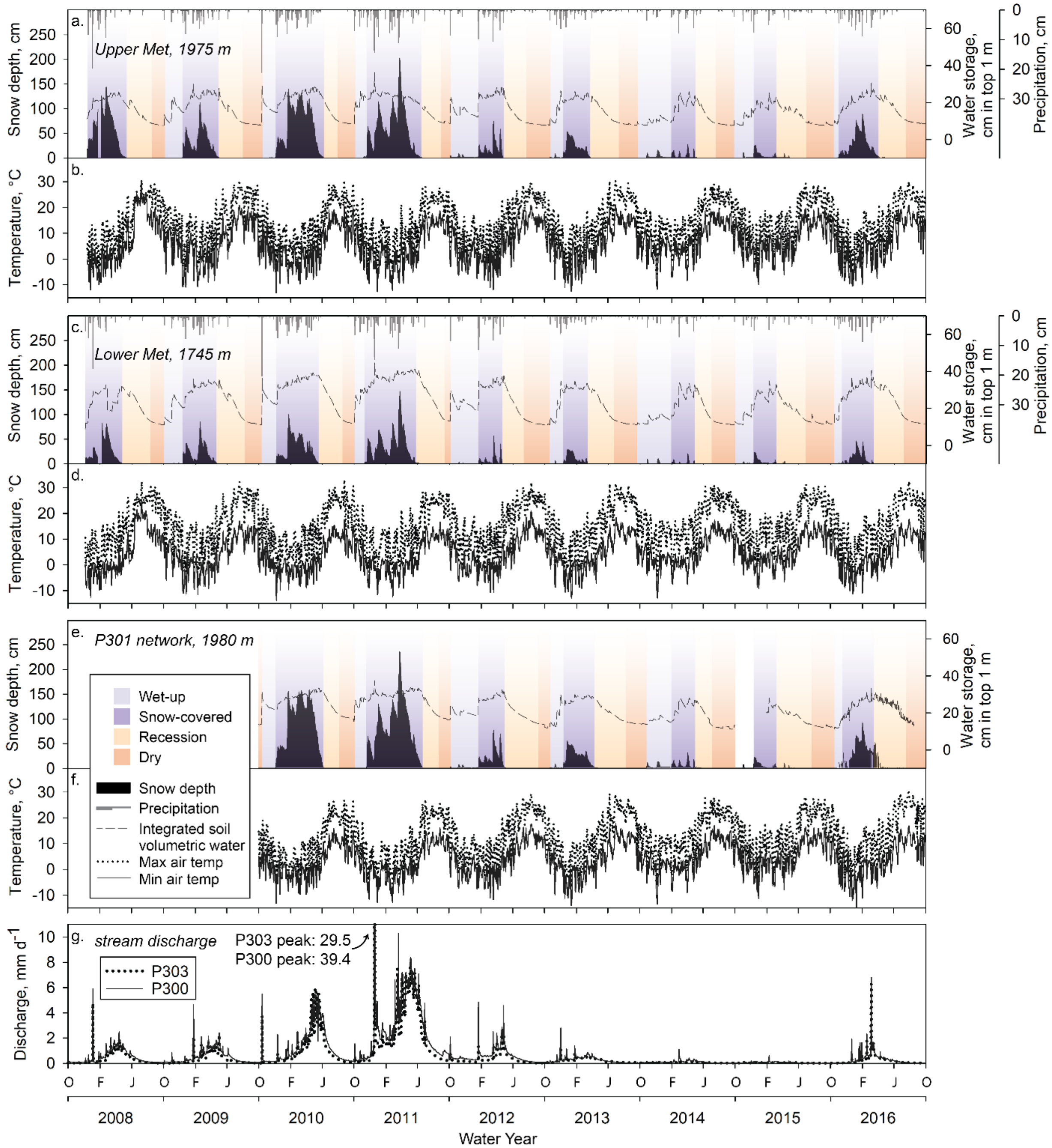

5 **Figure 4. Partial record of (a, c, e) precipitation (black bars), soil moisture (dashed lines), and snow depth (black shaded area), and (b, d, f) maximum and minimum air temperature (dotted and solid lines) at the Upper and Lower Met stations and P301 sensor network, and (g) stream discharge at subcatchment P303 and the integrating P300 catchment. Background colors in (a,c,e) generally indicate periods of wet-up, snow-coverage, soil moisture recession, and dry.**

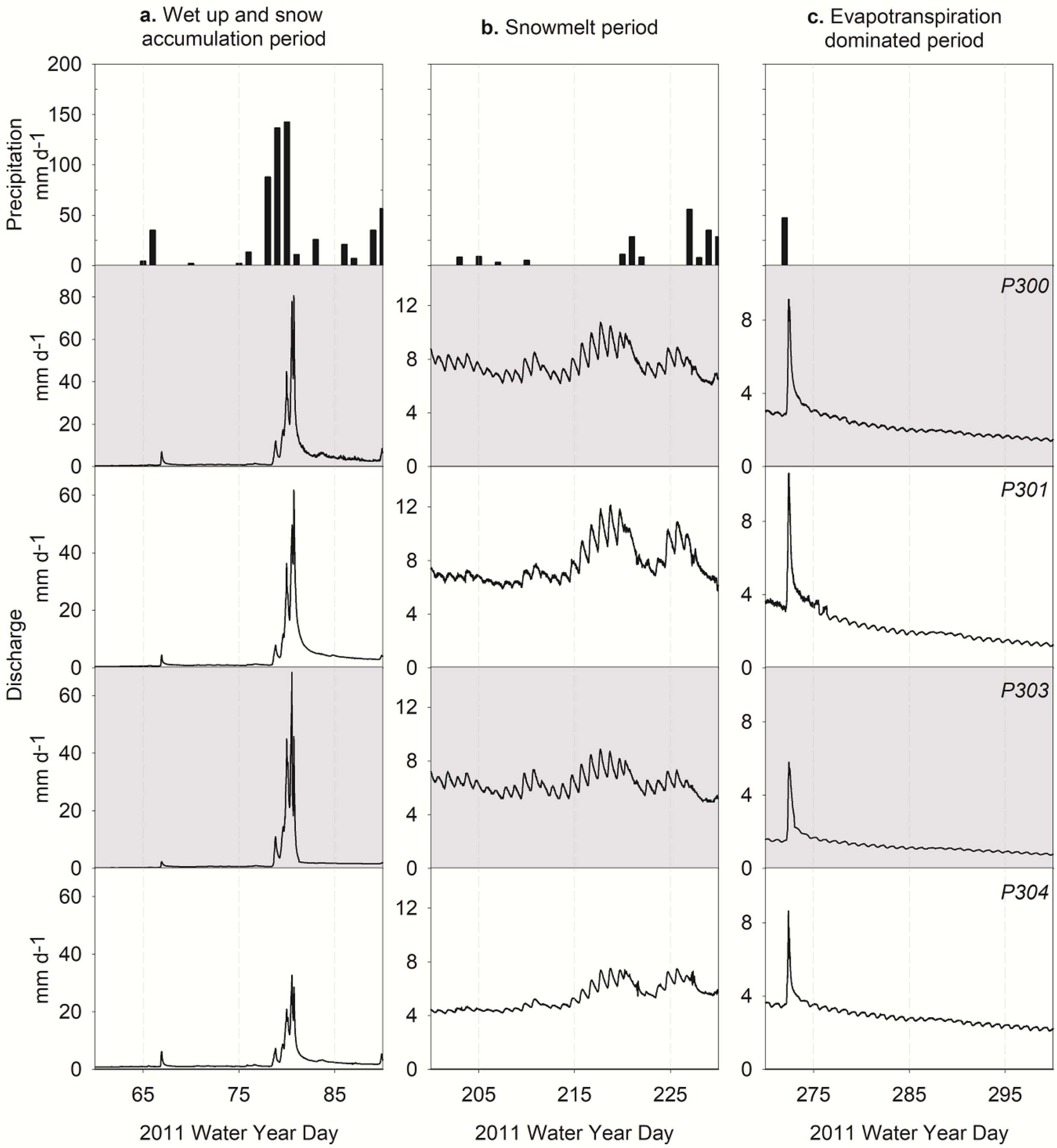

Figure 5. Selected 30-day periods in Water Year 2011 show hourly patterns in discharge for periods dominated by (a) incoming precipitation during an early season storm, (b) snowmelt, and (c) a mid-summer storm during the evapotranspiration-dominant period.

5