

# The NOAA Hydrometeorology Testbed Soil Moisture Observing Networks: Design, Instrumentation, and Preliminary Results

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## ABSTRACT

The NOAA Hydrometeorology Testbed (HMT) program has deployed soil moisture observing networks in the watersheds of the Russian River and the North Fork (NF) of the American River in northern California, and the San Pedro River in southeastern Arizona. These networks were designed to serve the combined needs of the hydrological, meteorological, agricultural, and climatological communities for observations of soil moisture on time scales that range from minutes to decades.

The networks are a major component of the HMT program that has been developed to accelerate the development and infusion of new observing technologies, modeling methods, and recent scientific research into the National Weather Service (NWS) offices and to help focus research and development efforts on key hydrological and meteorological forecast problems. These forecast problems are not only of interest to the NWS, but they also play a crucial role in providing input to water managers who work at the national, state, and local government levels to provide water for human consumption, agriculture, and other needs.

The HMT soil moisture networks have been specifically designed to capture the changes in soil moisture that are associated with heavy precipitation events and runoff from snowpack during the melt season. This paper describes the strategies used to site the networks and sensors as well as the selection, testing, and calibration of the soil moisture probes. In addition, two illustrative examples of the data gathered by the networks are shown.

The first example shows changes in soil moisture observed before and during a flood event on the Babocomari River tributary of the San Pedro River near Sierra Vista, Arizona, on 23 July 2008. The second example examines a 5-yr continuous time series of soil moisture gathered at Healdsburg, California. The time series illustrates the transition from a multiyear wet period to exceptionally dry conditions from a soil moisture perspective.

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## 1. Introduction

One of the key elements involved in flood forecasting is the amount of water stored in the soil prior to the onset of a heavy precipitation event (Opitz et al. 1995). When the soil in a watershed is dry, water absorption by the soil can significantly reduce the amount of precipitation

making its way into streams and rivers. However, in cases where the soil is saturated or has a low water storage capacity, nearly all of the precipitation making its way to the ground can become runoff. Heavy convective events of short duration can cause disastrous flooding (Caracena et al. 1979). If a number of previous precipitation events have saturated the soil in a particular watershed, a long-lived convective event occurring over the same area can also lead to massive destructive flooding (Bosart and Sanders 1981).

The increased demand on our limited water resources for human and agricultural uses has created a need to

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understand the role soil plays in storing water and controlling the amount of water available for aquifer recharge. Thus, soil moisture observations are being utilized by water resource managers in their long- and short-term management of water storage facilities (i.e., dams and reservoirs). Our ability to make accurate long-term observations of soil moisture on regional scales can also have a large impact on our ability to understand the impact of global climate change on our water supply.

Providing timely weather, hydrological, and climatological forecasts and warnings to the public that can be used to protect lives and property is the primary mission of the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS). In support of this mission the NOAA Earth System Research Laboratory (ESRL) and the NWS have developed the Hydro-meteorology Testbed (HMT) program. HMT has been developed as a means for accelerating the development and infusion of new observing technologies, modeling methods, and scientific results from the research community into the daily forecasting operations of the NWS River Forecast Centers (RFCs) and Weather Forecast Offices (WFOs) (Ralph et al. 2005; <http://hmt.noaa.gov>). The HMT networks have been conceived and deployed in a manner that attempts to address the combined observational soil moisture needs of several partners in the research, NWS operations, climate, agricultural, state government, and water resource management communities.

Historically, soil moisture measurements have been developed and used by soil physicists in their research and by the agricultural industry to maximize the benefits of irrigation. Understanding the role of soil water physics on both hydrological forecasts of river flows and meteorological forecasts of precipitation and planetary boundary layer development has been hindered by the lack of affordable and reliable soil water observational technology. In the last 10 years inexpensive and reliable soil moisture measuring instrumentation has become commercially available. Meteorologists and hydrologists are now beginning to explore the impact of soil moisture changes on forecasts made using both medium-range and mesoscale numerical weather prediction and hydrological streamflow models.

Godfrey and Stensrud (2008) have utilized in situ soil moisture observations to show how errors in the initial soil state impact the accuracy of mesoscale meteorological forecasts made using the NOAA–National Centers for Environmental Prediction (NCEP) North American model (Janjic 2003). Clark and Hay (2004) also show that river basin initial soil states play a major role in the accuracy of streamflow forecasts driven in part by the NCEP Medium-Range Forecast (MRF) products. Both of these NCEP numerical weather prediction systems

use the Noah land surface model (LSM) (Chen and Dudhia 2001; Koren et al. 1999) to specify the model's land surface initial temperature and moisture state. The partitioning of the sensible and latent heat fluxes that drive the planetary boundary layer in the meteorological models relies heavily on an accurate specification of soil moisture.

Currently, the lack of routine observations of soil moisture at temporal and spatial scales suitable for meteorological data assimilation has made it necessary for the Noah LSM to continuously cycle the temperature and soil moisture fields in the LSM with additional input from radar-estimated and rain gauge-measured precipitation. Thus, the Noah LSM initial soil water state is not specified using actual soil moisture measurements (Godfrey and Stensrud 2008).

The conceptual rainfall-runoff model used in forecast operations by the National Weather Service RFCs to forecast streamflow is the Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash 1995). The accuracy of this model depends heavily on “expert” manual calibration (Hogue et al. 2000). Calibration must be carried out in part because physical soil processes are not part of the model. Koren et al. (1999) have developed a method of parameterizing soil processes in the SAC-SMA model based on estimates of soil heat flux. Testing and evaluating the Sacramento Soil Moisture Accounting Heat Transfer (SAC-HT) model have increased the demand for soil moisture observations.

Currently the Oklahoma Mesonet (Illston et al. 2008), the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN) (Schaefer et al. 2007), and the USDA Agricultural Research Service (ARS) Walnut Creek Watershed (Renard et al. 1993) networks represent some of the major efforts being made to deploy observational soil moisture and instrumentation on a river basin and on a national scale. These networks have been designed to gather data on time scales acceptable for evaluating the accuracy of medium- and short-range meteorological models and carrying out climate impact studies. The HMT soil moisture networks have been configured to support monitoring temporal soil moisture changes associated with convective activity and flash flooding in addition to climatological studies.

In situ soil moisture observations also play an important role in the development of remote sensing techniques that measure soil moisture. Direct measurement can be used to assess the accuracy and limits of satellite, cosmic ray (Zreda et al. 2008), and airborne soil moisture observations.

Section 2 describes the locations, geology, soil textures, and scientific objectives of the California and

Arizona HMT soil moisture networks. Section 3 describes the instrumentation and calibration methods utilized in the HMT soil moisture observational networks. In section 4, a preliminary analysis of a flash flood case observed on the Babocomari River tributary of Arizona's San Pedro River is shown. A 5-yr soil moisture climatology measured in the Russian River basin is presented in section 5. The summary and conclusions are presented in section 6.

## 2. The HMT soil moisture networks

### a. Russian and American River basin networks

The first HMT soil moisture observational network was deployed to support early HMT studies along the Coast Range and within the Russian River basin of California. These studies focused primarily on the impact of heavy precipitation events that occurred as strong winter storms made landfall along the northern Pacific Coast. Beginning with the winter of 2005/06, HMT shifted its focus farther east toward the Sierra Nevada and the North Fork (NF) of the American River basin. The current HMT soil moisture observational network consists of three legacy stations that remain in the Russian River basin, nine stations located in the NF of the American River basin, one station in the Yuba River basin, and one observing site located near Lake Tahoe.

The Russian River legacy stations are located at Cazadero (CZC), Rio Nido (ROD), and Healdsburg (HBG) (Fig. 1a; Table 1). The NF American River basin stations are located at Alta (ATA), Blue Canyon (BLU), Colfax (CFX), Canada Hill (CNH), Foresthill (FHL), Greek Store (GRK), Onion Creek (OCR), Sugar Pine (SGP), and Talbot (TBT). Big Bend (BBD) is in the headwaters of the Yuba River basin and Ward Creek (WDC) drains directly into Lake Tahoe. (Fig. 1b; Table 1). Early American River HMT research efforts focused on studying the elevations where radar bright bands indicated that mixed microphysical processes were present in the clouds. Thus, the 2004–06 deployments targeted areas in the American River basin below 1200 m MSL. Recent soil moisture instrumentation deployments have focused on higher elevations and the Middle Fork (MF) of the NF of the American River.

The soils present in the American River basin are of three basic types. Below approximately 1200 m MSL the soils consist of sandy clay loams. The origin of these soils can be traced to the ancient seabed that overlaid the granite batholith that formed the Sierra Nevada when it pushed up from the mantle. The Alta, Colfax, Foresthill, Sugar Pine, and Blue Canyon soil sensors are located in this basic soil classification. At higher elevations the soils

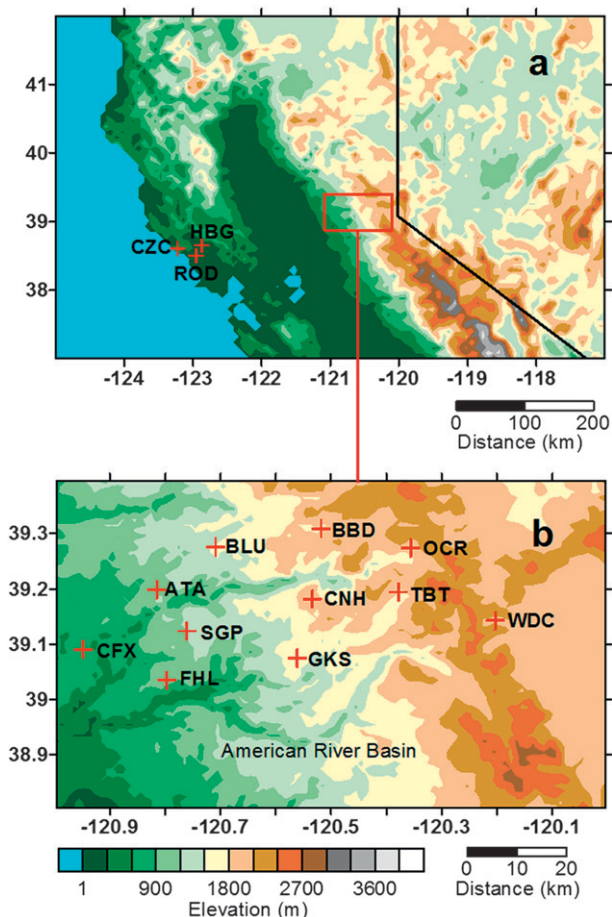


FIG. 1. HMT-West soil moisture observing network (a) Russian and American River basins and (b) expanded view of the American River basin. Red crosses denote the soil moisture station locations.

are composed of alluvial glacial debris. These soils were formed by the action of glaciers and aeolian processes on the exposed batholith and the rocks that were formed by the volcanism that accompanied the upward thrust of the batholith. The Greek Store, Onion Creek, Talbot, Canada Hill, and Big Bend stations are all located in either alluvial or volcanic soil classifications. Thus, the soil moisture sensors in the upper and lower portions of the NF of the American River basin have been placed in a way that should allow us to quantify the effect of soil type on basin drainage as a function of elevation.

### b. The Arizona HMT Soil Moisture Observational Network

The Arizona HMT Soil Moisture Observational Network consists of six stations located in the Babocomari tributary of the San Pedro River basin (Figs. 1a,b; Table 1). The stations are located at Canelo (CNL), Black Oak Cemetery (BOC), Freeman Spring (FMS),

TABLE 1. HMT soil moisture site locations, measurement depths, and installation dates.

Location	ID	Lat (°)	Lon (°)	Elev (m)	Soil probe depths (cm)	Installation date
Healdsburg, CA	HBG	38.65	-122.87	62	10, 15	12/29/03
Blue Canyon, CA	BLU	39.28	-129.71	1610	10, 15	10/1/05
Cazadero, CA	CZC	38.61	-123.22	475	10, 15	11/15/05
Alta, CA	ATA	39.20	-120.82	1085	10, 15	11/16/05
Colfax, CA	CFX	39.09	-120.95	725	10, 15	11/20/05
Foresthill, CA	FHL	39.04	-120.80	1042	10, 15	1/7/06
Boulder, CO	SKG	39.99	-105.26	1679	5, 10, 15, 20, 50	6/27/06
Rio Nido, CA	ROD	38.51	-122.96	30	10, 15	12/2/06
Onion Creek, CA	OCR	39.27	-120.36	1886	10, 15	10/17/07
Greek Store, CA	GKS	39.08	-120.56	1728	10, 15	10/18/07
Sugar Pine, CA	SGP	39.12	-120.76	1158	10, 15	10/19/07
Canada Hill, CA	CNH	39.18	-120.53	2020	10, 15	10/21/07
Talbot, CA	TBT	39.19	-120.38	1780	10, 15	10/24/07
Big Bend, CA	BBD	39.30	-120.52	1739	10, 15	12/1/07
Freeman Spring, AZ	FMS	31.57	-110.55	1537	5, 10, 20, 50, 100	5/20/08
Canelo, AZ	CNL	31.55	-110.52	1505	5, 10, 20, 50, 70	5/21/08
Elgin, AZ	ELG	31.59	-110.51	985	5, 10, 20, 30, 50	5/22/08
Whetstone, AZ	WSE	31.69	-110.28	1277	5, 10, 15, 20, 50	5/25/08
Black Oak, AZ	BOC	31.56	-110.54	1556	5, 10	5/28/08
Ward Creek, CA	WDC	39.14	-120.20	2012	10, 15	11/21/08

Elgin (ELG), Whetstone (WSE), and Fairbank (FBK). The San Pedro River supplies a large portion of the agricultural water used in southeastern Arizona and is a major recharger of the aquifers that provide Ft. Huachuca and Sierra Vista, Arizona, with drinking water (Fig. 2). In addition, during the North American Monsoon, heavy precipitation events in the San Pedro River can cause significant flooding along the river.

One of the objectives of the Arizona HMT Soil Moisture Network is to provide an observational dataset that can be used in the evaluation and refinement of the hydrological models used operationally by the NWS. Stations were placed from the headwaters of the Babocomari River down to the location where it joins the main channel of the San Pedro River (Fig. 3).

River basins in the NWS distributed hydrological models are broken down into individual cells that contain the channeling or connectivity of the streams in the cell along with the cell's ability to transmit water from the surface into the water table or into the streams. This grid system is known as the Hydrologic Rainfall Analysis Project (HRAP) grid coordinate system (Reed and Maidment 1999). Each HRAP cell covers approximately 16.0 km<sup>2</sup> of a river basin. Thus, the stations located at CNL, FMS, and BOC are designed to capture the heterogeneity of soil processes that are operating at scales smaller than the HRAP scale.

The soils in southeastern Arizona are dominated by alluvial fan material, volcanic debris, and extensive layers of limestone conglomerate know as caliche. In this region, caliche can be found anywhere between the surface of the earth and 1.0 m below.

### c. Boulder, Colorado

There is also a soil moisture station collocated with the NWS Denver WFO and NOAA/ESRL in Boulder, Colorado (SKG). This station supports the hydrologic outlooks issued by the WFO and ongoing evaluation of

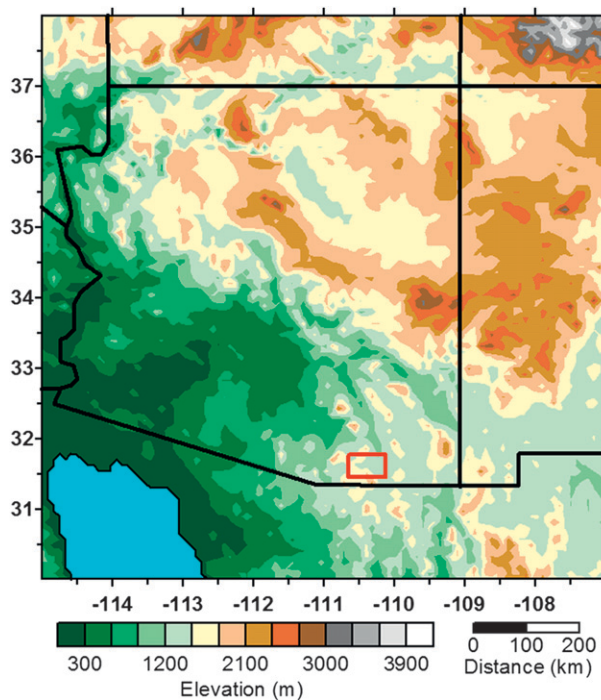


FIG. 2. State of Arizona. Area outlined in red is the location of the HMT-Arizona Soil Moisture Network.

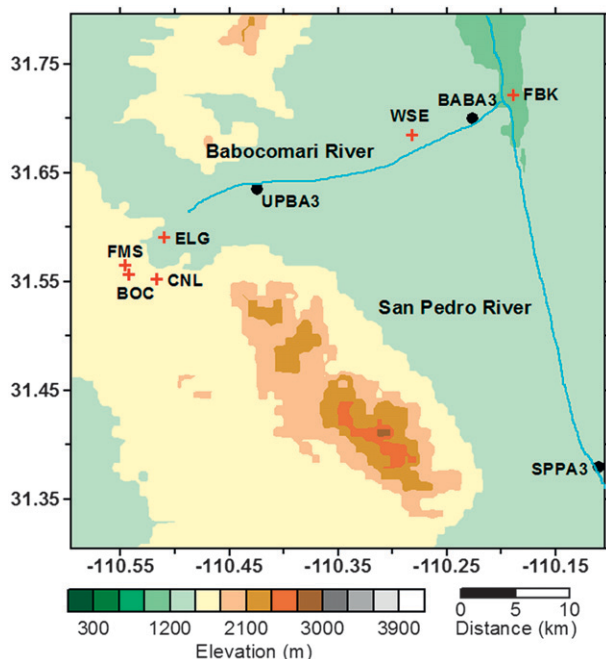


FIG. 3. HMT-Arizona Soil Moisture Network. Red crosses show the locations of the soil moisture observing stations; circles denote the locations of the river gauge stations.

the robustness and accuracy of the soil moisture sensors utilized by NOAA/Earth System Research Laboratory (ESRL).

### 3. Instrumentation and calibration

#### a. Instrumentation

Soil moisture observations are made using Campbell Scientific, Inc. (CSI), CS616 soil water content reflectometers or Stevens Water Hydra Probes. A detailed description of the soil moisture instrumentation and calibration methods is presented later in this section. Soil probe burial depths in the Californian HMT network have been standardized at 10 and 15 cm below the surface. In Arizona we have attempted to use the USDA/SCAN probe depths of 5, 10, 20, 50, and 100 cm. However, one can encounter caliche or bedrock at shallower depths in southeastern Arizona. At those locations probes are placed at USDA/SCAN depths starting at 5.0 cm and continuing downward until bedrock or caliche is encountered. The deepest probe is then placed in the soil adjacent the rock layer (Fig. 4). All soil probes are placed horizontally in the soil.

Soil temperature observations are taken at each probe depth using T-107 temperature probes. The temperature data are used for climatological studies and

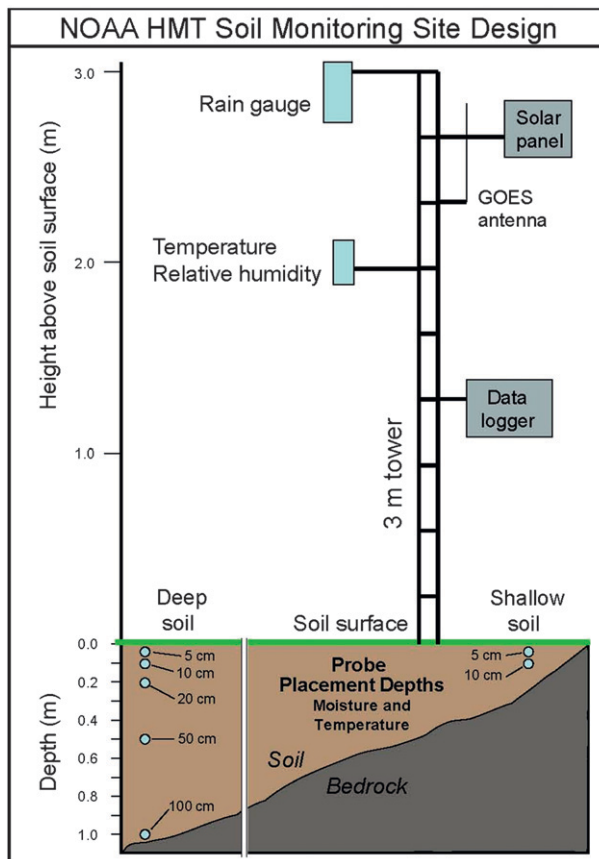


FIG. 4. Schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station.

applying soil temperature corrections to the reflectometer measurements.

All of the soil moisture stations deployed by NOAA/ESRL measure air temperature and relative humidity at 2.0 m using Vaisala HMP-45C probes. The air temperature and relative humidity measurements are deployed at the soil moisture observing locations to support other aspects of the HMT program. Precipitation measurements are made using Texas Electronics tipping-bucket rain gauges, Met One heated tipping-bucket rain gauges, or Noah II weighing precipitation gauges. The choice of precipitation gauge depends on the phase and fall rate of the precipitation expected at each location. Table 2 summarizes the instrumentation used at the soil moisture observational locations along with the accuracies of the instruments supplied by the manufacturers.

The soil observing stations are queried at hourly intervals over a voice telephone line from a central data collection/archiving system operated by NOAA/ESRL in Boulder or the station data are transmitted using Geostationary Operational Environmental Satellite (GOES)

TABLE 2. Instrumentation deployed in the HMT soil moisture networks.

Variable	System	Type	Accuracy
Air temperature	Väisälä HMP-45C	Thermistor	$\pm 0.4^{\circ}\text{C}$
Relative humidity	Humicap	Capacitor	$\pm 2\%$ (0%–90% RH) $\pm 4\%$ (90%–100% RH)
Precipitation	Texas Electronics	Tipping bucket	$\pm 1\%$ (Up to $0.254 \text{ mm h}^{-1}$ ) 0, $-3\%$ ( $25.4\text{--}50.8 \text{ mm h}^{-1}$ ) 0, $-5\%$ ( $50.8\text{--}76.2 \text{ mm h}^{-1}$ )
Precipitation	Met One	Tipping bucket	$\pm 0.5\%$ ( $12.7 \text{ mm h}^{-1}$ ) $\pm 1.0\%$ ( $25.4\text{--}76.2 \text{ mm h}^{-1}$ )
Precipitation	Noah II	Weighing-type gauge	$\pm 0.254 \text{ mm h}^{-1}$
Soil temperature	CSI T107	Thermistor	$\pm 0.4^{\circ}\text{C}$ (worst case)
Soil wetness	CSI CS616	Reflectometer	$\pm 2.0\%$
Soil wetness	Stevens Water Hydra Probe	Frequency domain reflectometer	$\pm 3.0\%$

transmitters located at the observing sites to the NOAA GOES data collection center located at Wallops Island, Virginia. The data from the GOES-equipped soil moisture observational sites are then retrieved from Wallops Island by the Boulder data collection system. Six of the NOAA/ESRL soil moisture stations use GOES data links. The provisional data are made available in near-real time (1-h latency) to the NWS RFCs, WFOs, and NCEP via FTP in addition to being available in both graphical and numerical form on the NOAA/ESRL Web server (see <http://www.esrl.noaa.gov/psd/data/>) located in Boulder.

Currently the HMT-West datasets are ingested by the NWS California Nevada RFC (CNRFC) and the NWS WFO located in Monterey, California. The Arizona datasets are ingested by the NWS Colorado basin RFC (CBRFC). In collaboration with CBRFC the Arizona stations have been assigned NWS Handbook 5 identification numbers and the precipitation data gathered by the stations are used in the generation of the NWS Multisensor Precipitation Estimates (MPE) product over southeast Arizona.

The workhorse of the HMT soil moisture observing networks has been the CS616 Water Content Reflectometer. The strengths of the CS616 are its relatively low cost, long-term stability, and low power consumption. The probes have been used successfully by the United States Geological Survey (USGS) in modeling studies of snowpack melting and bedrock infiltration rates (Flint et al. 2008).

However, the probe does have some drawbacks. Placing the 30-cm-long probe rods in cobble soils can be difficult and, as we will show in the Babocomari River basin, nearly impossible at some locations. Because the probe rods also serve as antennas, probes placed within 22.8 cm of each other can return erroneous results if they are enabled and sampled simultaneously. This requires each probe to use a separate control channel on

a datalogger, somewhat limiting the number of probes that can be used at an observing site. In addition, at locations near cell phone towers or GOES transmitters we have observed spurious signals that we attribute to radio frequency (RF) signals picked up by the CS616s during their sampling period.

The “delta function”-like behavior of these spikes makes it difficult to distinguish between abrupt changes in soil moisture caused by the onset of precipitation or snowmelt and electrical noise (Fig. 5a). However, we have found that RF-induced spikes in the dataset are of short duration, affecting fewer than two average soil moisture data values. The statistical properties of the spikes make it possible to remove the majority of the spikes from the dataset in postprocessing using a median filtering algorithm. We subjected the time series shown in Fig. 5a to a five-point median filter. Each data point in the time series has been replaced by the median value found in the five-point window that includes the value in question and two points on either side of the point. The leading and ending two points in the time series are untouched by the filter.

The filter method we have chosen appears capable of removing the RF noise while preserving abrupt changes in soil moisture caused by precipitation and snowmelt. Dry-down periods and small-amplitude diurnal cycle changes in soil moisture are also unaffected (Fig. 5b). Errors in reflectometer data caused by RF noise can induce a bias in soil moisture data gathered using an hourly or daily averaging interval. Our ability to minimize this type of error in soil moisture estimates has been made possible by the high temporal sampling rate that we use to measure the period. Note that the amplitude of the spikes in the reflectometer period yields volume water content (VWC) values that are well under the  $\pm 2.5\%$  accuracy specification for the CS616 provided by CSI (Campbell Scientific 2010). Volumetric water content is defined as

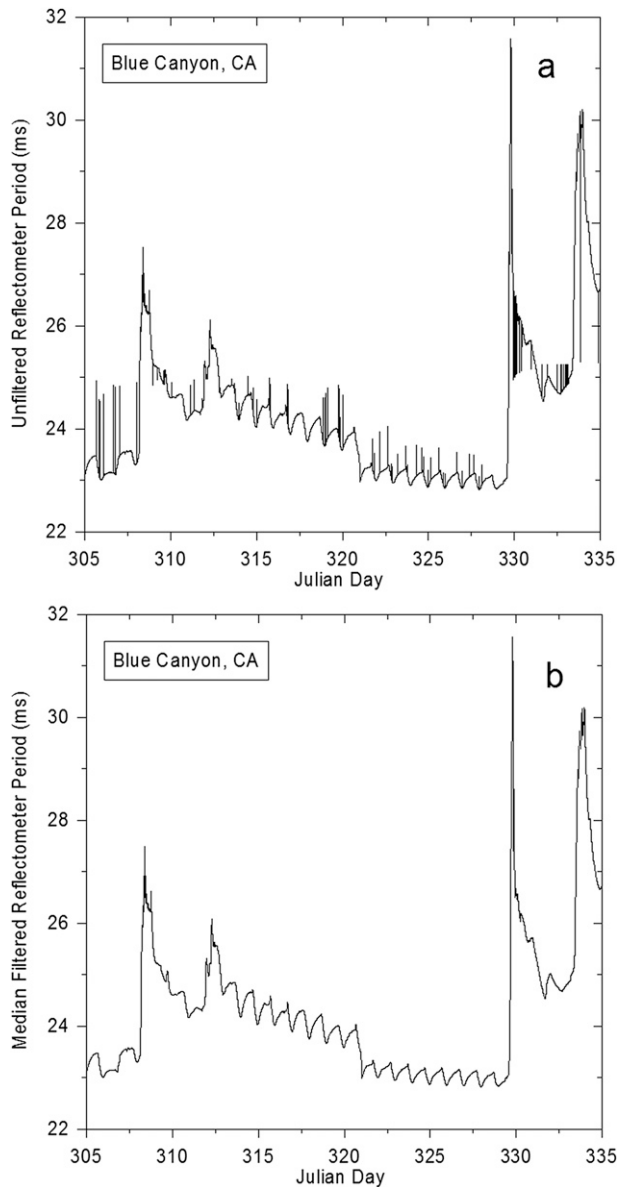


FIG. 5. Blue Canyon reflectometer output period time series (a) before and (b) after median filtering.

$$VWC = \frac{V_w}{V_t} \times 100, \tag{1}$$

where  $V_w$  is the volume of water and  $V_t$  is the total (bulk) soil volume. The soil volumetric wetness fraction is simply  $VWC/100$ .

Because the 30-cm-long probe rods of the CS616 can be difficult to place in cobble soils, we have begun testing and implementing the Stevens Water Hydra Probe into the HMT soil moisture observing networks. The 6.0-cm probe rods of the Hydra Probe sensor make it easier to make probe placements in cobble soils. The

Hydra Probe has been used in both the USDA/SCAN and USDA/ARS Walnut Creek Experimental Watershed soil moisture observational networks (Kennedy et al. 2003). The Hydra Probe uses frequency-domain reflectometer (FDR) methods to infer VWC and the electrical conductivity of the soil within the probe sampling volume.

Traditionally, gravimetric sampling using soil cores has been used to determine soil VWC (Hillel 1998) and calibrate soil VWC measurement systems. The method (while error-prone), which requires oven drying soil core samples, is typically used to calibrate probes that measure soil moisture. Errors can arise from sampling, transporting, and weighing the samples before and after drying. The process of obtaining soil core samples destroys the natural state of the soil around the sampling area, and great care must be taken to minimize the disturbance. Gravimetric sampling also requires intensive manual labor, which makes the procedure costly from an economic point of view.

*b. Calibration*

Our experience has shown that the default calibrations supplied by CSI can introduce errors in the VWC measurements made using the reflectometers. Optimum results have been obtained when calibration functions are derived for each soil type sampled by the CS616 using gravimetric sampling. Conclusions similar to ours for the Stevens FDR probes have been reported by Kennedy et al. (2003) and Brock et al. (1995).

Therefore, we adopted a calibration procedure for all the HMT soil moisture observing stations. After the probes have been placed in the wall of the soil pit, soil cores are extracted from the adjacent walls of the pit. If the soil through the depth of the pit is uniform, three to five ~50-g soil cores are taken at a single sampling depth. If multiple soil horizons are present and a soil probe is located in one of those horizons, additional cores are removed at that depth. The soil cores are then dried as soon as possible using a Denver Instruments Laboratory IR-50 infrared moisture analyzer at the standard temperature of 105°C. After recording the moist and dry weights of the cores, the cores are checked for rocks or excessive organic material. The bulk density and VWC are then calculated for the uncontaminated cores. This procedure is repeated periodically at each soil moisture site during the annual precipitation cycle in an attempt to capture expressively dry and moist soil conditions. Every effort is made to preserve the soil state of the site and at the same time extract soil cores that are representative.

Finally, a regression analysis is calculated that provides us with a calibration function for each soil type that has been found at an observing location. In addition, the

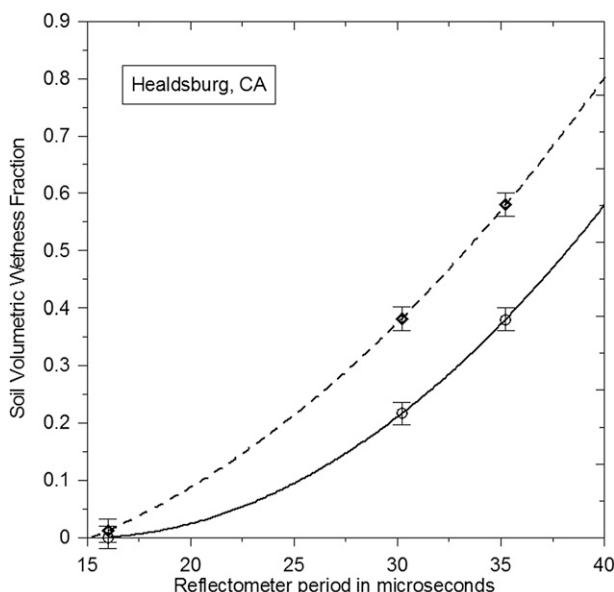


FIG. 6. NOAA/ESRL-derived calibration vs CSI-supplied calibration. The dashed line indicates the CSI calibration curve. The solid line denotes the NOAA/ESRL calibration curve developed using in situ gravimetric sampling.

raw output period of the reflectometer is corrected for changes in soil temperature using T107 soil temperature probe data gathered at the same depth as the reflectometer using the procedure suggested by CSI (Campbell Scientific 2010). The dielectric properties of soil are weakly dependent on temperature. The correction attempts to minimize the impact of soil temperature on the CS616 reflectometer VWC observations.

Figure 6 shows the difference between the CSI-supplied calibration and calibrations derived using gravimetric sampling at our Healdsburg, California, observing location (Fig. 1a). The general calibration function that relates the output period of the reflectometer to VWC is assumed to be quadratic. As one can see, the calibration curve derived using the gravimetric samples taken at Healdsburg is flatter at the longer periods. According to documentation provided by CSI, the calibrations for the probes were derived in the laboratory using air-dried and saturated soils. The soils contained some silt and clay but were generally considered sandy loams with an electrical conductivity of  $\leq 0.5 \text{ dS m}^{-1}$  and a bulk density of  $\leq 1.55 \text{ g cm}^{-3}$ . CSI states that the reflectometer response can change when the soil electrical conductivity exceeds  $0.5 \text{ dS m}^{-1}$ . The USGS soils classification published for the area around the Healdsburg site indicate that the soil series is a Montara cobbly clay loam with clay content in the first 15.0 cm of 31.0% and a bulk electrical conductivity of  $1.0 \text{ dS m}^{-1}$ . We have found similar discrepancies between the CSI-supplied calibration and

those derived by NOAA/ESRL using the gravimetric method in soils that have high clay contents and/or an electrical conductivity  $\geq 0.5 \text{ dS m}^{-1}$  based on the USGS soil surveys.

This calibration procedure has limitations. Identifying soil layers where soil cores are extracted and the elimination of nonrepresentative cores after drying are carried out subjectively. The number of samples used in the initial regression analyses can be as few as six, and it may not be possible in the years following the site installation to capture the wettest and driest soil conditions using gravimetric sampling. NOAA/ESRL recalibrates the datasets periodically as new core samples are taken and included in the regression analyses. The data retained in the regression analyses are chosen subjectively to maximize the coefficient of determination.

### c. Data quality control

The site dataloggers are programmed to store 2-min averages of each variable measured at that location. Temperature-corrected soil moisture values are also calculated at each level using the site-specific calibration function and are included in the 2-min archive datasets along with the raw reflectometer period measurements. As mentioned earlier in the manuscript, the provisional data for each site are archived in Boulder and made available on the NOAA/ESRL Web site in near-real time.

The raw datasets are then used to create a quality-controlled dataset for each site. The raw reflectometer periods are subjected to median filtering and temperature-corrected soil wetness fractions are recalculated using the site calibration function. The data are then examined by NOAA/ESRL personnel and gross errors are removed manually. This task is repeated each water year. The quality-controlled datasets are made available to users upon request via FTP.

## 4. Flooding event observed by the Arizona HMT soil moisture network

NOAA/ESRL completed the installation of the HMT Arizona Soil Moisture Network (Figs. 2 and 3) during the month of May 2008 in anticipation of the 2008 North American monsoon. Late in the afternoon of 23 July 2008 a monsoon heavy rainfall event began. The evolution of the soil moisture volumetric wetness fraction measured at Whetstone, Arizona (Fig. 7), showed that earlier monsoonal precipitation had brought the soil between 10.0 and 20.0 cm to near field capacity (0.42) while the soil below 20.0 cm stayed considerably drier. Field capacities in this paper are estimated by examining the way a soil layer soil dries in the days following a significant precipitation event (Veihmeyer and



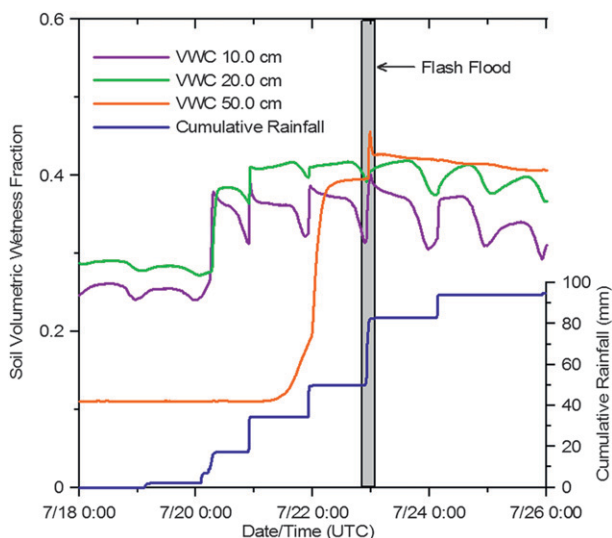


FIG. 7. Evolution of the cumulative precipitation, and soil wetness fractions measured at 10-, 20-, and 50-cm depth for the period 18–26 Jul 2008 at Whetstone, AZ.

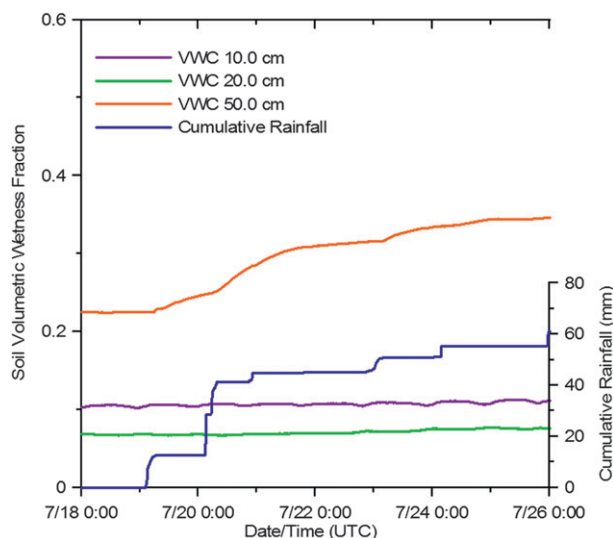


FIG. 8. As in Fig. 7, but at Elgin, AZ.

Hendrickson 1931; Hillel 1998). The water from the earlier precipitation events had been drawn into the deeper soil layers by gravity, and surface evaporation had managed to keep the shallower near-surface layers dryer. The stage for the flooding event on the Babocomari River was set by two monsoonal rainfall events occurring on 21 and 22 July.

A caliche layer was found 52.0 cm below the surface at Whetstone. This layer acts as a barrier that inhibits the ability of gravity to pull water deeper into the ground on time scales shorter than those of aquifer recharge. Thus, the precipitation from these events finally managed to saturate the entire depth of the soil column (Fig. 7) just before the 22–23 July 42.0-mm precipitation event. Soil wetness fractions observed higher in the basin at Elgin (Fig. 8) and Freeman Spring (Fig. 9) at 50.0 cm are considerably lower in the days following the 22 July precipitation event observed at Whetstone. Freeman Spring and Elgin did not receive precipitation on 22 July. The soil layer between 10.0 and 20.0 cm at both Freeman Spring and Whetstone was wetter than the same layer at Elgin. This is not surprising given that the precipitation measured at Elgin was nearly a factor of 2 lower than either Freeman Spring or Whetstone during the period. Soil conditions through the depth of the soil column were the wettest at Whetstone.

Precipitation measured near 0000 UTC 23 July at Freeman Spring, Elgin, and Whetstone suggests that the heaviest precipitation fell in the lower Babocomari River basin. If we assume that the Whetstone soil wetness observations characterized the soil conditions in the

lower Babocomari, then it is safe to conclude that most of the rain that fell during the afternoon of 23 July became surface runoff. The peak discharge at the river gauge station closest to Whetstone (USGS 0741400, NWS BABA3) (Fig. 3) occurred at 0000 UTC 23 July (Fig. 10). The discharge increased from 0.0 to  $118 \text{ m}^{-3} \text{ s}^{-1}$  in less than 15 min. Historically this is the second highest discharge recorded by the BABA3 gauging station. Our analysis suggests that soil wetness fractions as a function of depth and that the timing of precipitation events and precipitation amounts varied considerably in the over the river basin before the river flooded. It appears that the

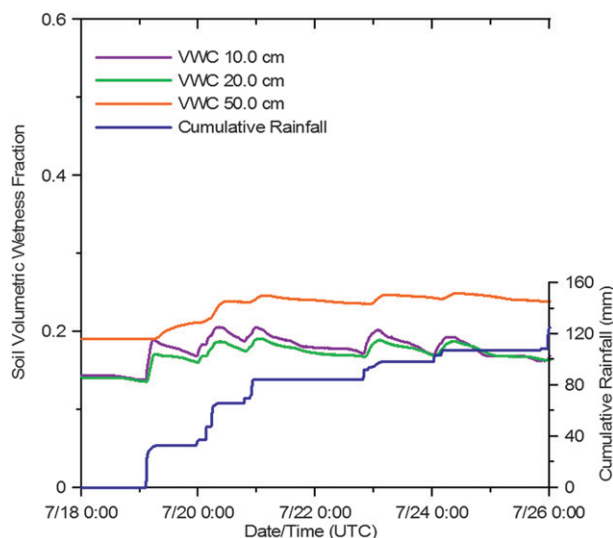


FIG. 9. As in Fig. 7, but at Freeman Spring, AZ.

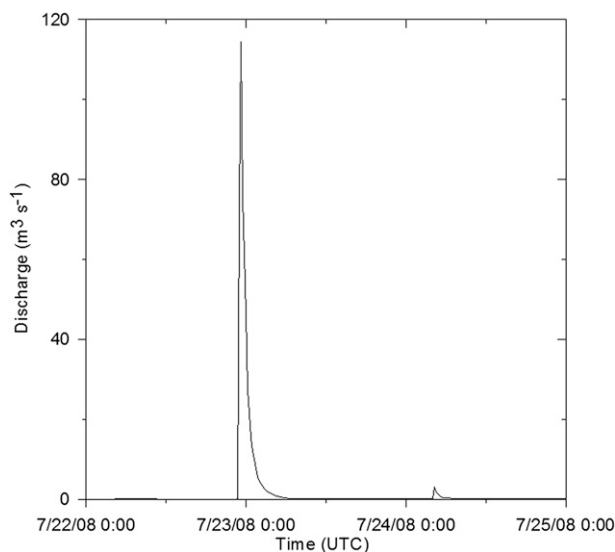


FIG. 10. Observed discharge as a function of time at USGS 09471400 (NWS BABA3), 5.4 km northwest and downstream of Whetstone (WSE) for the period 22–25 Jul 2008 (UTC).

heaviest rain fell in the lower basin on a soil column that was at or near saturation.

## 5. Soil moisture climatology

One of the objectives for the soil moisture networks is to create high-quality soil moisture records for climate and hydroclimate studies of drought, and other water cycle–related phenomena. To illustrate these future uses, the longest continuous time series from the networks is shown in Fig. 11. It is from a site near Healdsburg, California, that was installed in late 2003 at a depth of 10 cm.

The annual cycle of moistening in the fall, followed by short peaks that represent individual rain events and then by a rapid drying in the spring, is evident. As the dry season progresses each year, there is then a period of more gradual drying that culminates with the beginning of the next wet season. The rain events in the fall gradually moisten the soil to greater than 0.38 (i.e., its “field capacity”) through a series of two to four wet events, after which the soil moisture does not increase beyond roughly 0.55. This transition season typically lasts several weeks, as the soil absorbs the early-season precipitation before storms have a greater impact on runoff.

By collecting measurements over several years it is possible to identify phases and transitions that occur each season and then diagnose trends in those characteristics. An example is shown in Fig. 11 that focuses on the length of the wet seasons and of the dry seasons, which are relatively well defined in the climate of the

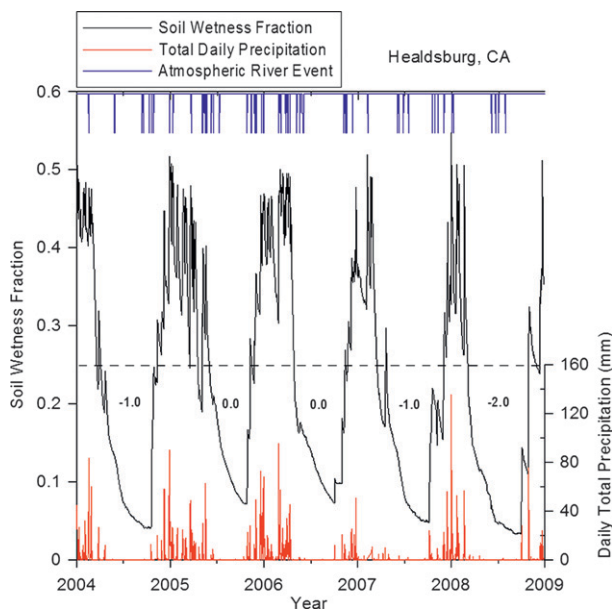


FIG. 11. A 5-yr soil wetness fraction climatology (black), daily total precipitation (red), and atmospheric river events (blue). The dashed line indicates a soil wetness fraction of 0.25. Palmer drought indices are shown in bold type.

region. To illustrate this, a specific soil wetness fraction (0.25) is selected that roughly separates the period of rapid drying during spring from the period of slower drying thereafter (Fig. 11). This value also conveniently separates the “wet” and “dry” seasons from a soil moisture perspective at this site. The trend in wet season duration is evident, dropping steadily from 263 days in the 2004/05 wet season to 225, 206, and 162 days in the ensuing years. Conversely, the dry season grew from 106 days in 2005 to 225 days in 2008. During this 4-yr period, the minimum soil wetness fraction dropped from 0.07 to 0.03, another indication of the cycle of dryness that has struck this region. One impact of this extended period of increasing dryness is that the forests, which depend on the soil moisture, became exceptionally vulnerable to major fires. This vulnerability was exposed when an unusual series of summer thunderstorms struck the Russian River region in June 2008, igniting many wildfires. Interestingly, by 2008 the dry season had reached 225 days in length, exactly the length the wet season had been just 3 years before. In addition, the Palmer drought index values are also correlated with the length of the winter precipitation period (Fig. 11).

These new data provide a useful quantitative perspective on the changes in soil moisture during individual seasons, as well as trends in water cycle–relevant phases across several years. The Healdsburg observations show that the high-temporal resolution data gathered by the HMT networks can also be used in climate analysis.

## 6. Summary

This paper describes the scientific goals, design, implementation, and preliminary results from the soil moisture networks that support NOAA's HMT Program. The HMT soil moisture observing networks have been designed specifically to gather soil moisture data on both subhourly and climatological time scales. The high-resolution data aspect of the HMT networks has been implemented to supply soil moisture data for the immediate and future needs of the NOAA NWS RFCs, NOAA NWS Office of Hydrologic Development (OHD), NOAA NWS NCEP, NOAA Research, and HMT partners. These needs include initialization and verification of the LSMs used in the medium- and short-range meteorological forecast models, validation of lumped and distributed hydrological models, flash flood forecasting, and the evaluation of both quantitative precipitation estimation (QPE) and quantitative precipitation forecast (QPF) products produced by the NWS.

We conclude that inexpensive, commercially manufactured, time-domain reflectometers can provide accurate measurements of soil VWC, given careful attention to the calibration and placement of the sensors. The simple calibration methods used for these networks have been outlined. Utilization of small, multiple soil samples reduces the destructive impact of gravimetric sampling on the land surface. The sensors have performed adequately in deep clay, cobble clay loams, and alluvial and volcanic soils.

Hydrometeorological conditions before and during the 23 July 2008 flood event on the Babocomari River have been examined using the HMT Arizona soil moisture observing network. The observations documented basin-scale variability in soil wetness as a function of depth and precipitation. In addition, the high temporal sampling rates used show that the response of the soil can occur on time scales that are not adequately resolved by soil moisture networks that sample either at daily or hourly intervals.

## 7. Suggestions for future research

One of the major operational goals of the NWS is to provide the most accurate forecasts of flooding that are possible. This is an enormous task that cannot be addressed adequately without accurate "forcing" information, such as QPF and QPE. However, improving and evaluating the performance of the current NWS hydrological models and developing the next generation of physically based hydrological models will also depend upon having accurate observations of soil moisture. Future work in this area should include developing

methods of assimilating observed soil moisture into both SAC-type river runoff models and the more physically based soil models under development at NOAA OHD and NCEP.

Another important topic that can be addressed using observational soil moisture data on both the basin and HRAP scale is the question of soil moisture heterogeneity. In other words, how many soil moisture observations are needed to characterize a river basin and the response of its smaller tributaries to precipitation? This is one of the goals of HMT.

Finally, hydrological forecasts provide water managers and dam operators with crucial inputs into their decision-making processes concerning the storage and release of water from reservoirs. In partnership with the California Department of Water Resources, NOAA-HMT is working to deploy soil moisture sensors at existing rain gauge sites across the state of California. This new dataset should be used to further evaluate the soil heterogeneity question and to assess the impact of assimilating soil moisture data into the Noah LSM on such a large scale. It will also provide new information relevant to detecting and predicting changes in regional climate and their impact on the water cycle from droughts to floods.

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