Long-term meteorological and soil hydrology database, Walnut Gulch Experimental Watershed, Arizona, United States

T. O. Keefer,[1] M. S. Moran,[1] and G. B. Paige[2]

Received 2 November 2006; revised 28 September 2007; accepted 20 December 2007; published 21 March 2008.

[1] A 17 year (1990–2006) meteorological and soil hydrology database has been developed for the Walnut Gulch Experimental Watershed in southeastern Arizona. Data have been acquired at three automated weather stations, 5 soil profile trench sites, and 19 locations dispersed across the watershed colocated with recording rain gauges. Meteorological elements measured at the weather stations include air temperature, relative humidity, wind speed, wind direction, barometric pressure, solar radiation, photosynthetically active radiation, and net radiation. Soil hydrology properties measured at the weather stations, trench sites, and rain gauges include soil moisture, soil temperature, soil heat flux, and soil surface temperature. Data are available at http://www.tucson.ars.ag.gov/dap.

Citation: Keefer, T. O., M. S. Moran, and G. B. Paige (2008), Long-term meteorological and soil hydrology database, Walnut Gulch Experimental Watershed, Arizona, United States, *Water Resour. Res.*, *44*, W05S07, doi:10.1029/2006WR005702.

1. Introduction

[2] Basic weather elements such as air temperature and solar radiation and soil hydrology elements such as soil moisture and soil temperature are required by natural resource and hydrologic managers and researchers for agricultural, planning, modeling and engineering applications. A network of automated weather stations (AWSs), soil profile trenches and near-surface soil hydrology sites colocated with rain gauges has been established on the USDA Agricultural Research Service, Southwest Watershed Research Center, Walnut Gulch Experimental Watershed (WGEW) to measure such elements since 1990. The Southwest Watershed Research Center (SWRC) has operated WGEW, located in the vicinity of Tombstone, Arizona, for more than 50 years [*Renard et al.*, 2008]. Ground-based observations of these elements are used for development and calibration of ecohydrological models [*Nouvellon et al.*, 2001; *Hymer et al.*, 2000], evaluation of soil hydrology sensing technology [*Paige and Keefer*, 2008], statistical characterization of soil hydrology networks [*Cosh et al.*, 2008; *Gebremichael and Vivoni*, 2008], ecohydrological studies [*Scott et al.*, 2000], and more recently for comparison with land, aircraft and satellite-based remote sensors [*Jackson et al.*, 2008; *Thoma et al.*, 2008]. A 17 year (1990–2006) meteorological and soil hydrology database has been developed for the WGEW from data acquired at the AWS, trenches and rain gauges. A description of this network and database is presented in this paper.

2. Walnut Gulch Experimental Watershed Meteorological and Soil Hydrology Network

2.1. Measurement Sites

[3] The meteorological and soil hydrology network consists of three automated weather stations (AWSs), five soil profile trenches and nineteen near-surface soil hydrology sites colocated with rain gauges (Figure 1 and Table 1). These measurement stations were established in collaboration with three different research projects at WGEW. Their locations were selected to meet the short-term needs of the projects and the long-term hydrologic research goals of SWRC. These stations have been maintained as an integral part of ecohydrological studies on WGEW.

[4] The five soil profile trenches and two of three AWSs are located at two intensive rangeland study areas that are representative of the two main vegetative covers on WGEW: the shrub dominated Lucky Hills (LH) subwatershed and the grass dominated Kendall (KEN) subwatershed [*Skirvin et al.*, 2008]. LH is a shrub plant community dominated by creosote bush (*Larrea divaricata*), whitethorn Acacia (*Acacia constricta*), mariola (*Parthenium incanum*), and tarbush (*Flourensia Cernua*) [*King et al.*, 2008]. The soil is Luckyhills series (coarse-loamy, mixed thermic Ustochreptic Calciorthids) with 3–8% slopes [*Heilman et al.*, 2008]. KEN is dominated by herbaceous vegetation, predominately black grama (*Bouteloua eriopoda*), sideoats grama (*Bouteloua curtipendula*), three-awn (*Aristida sp.*) and cane beard grass (*Bothriochloa barbinodis*) [*King et al.*, 2008]. The soils are a complex of soils, dominated by the Stronghold (coarse-loamy, mixed, thermic Ustollic Calciothids) with 4–9% slopes [*Heilman et al.*, 2008]. Soil descriptions and physical properties for other areas of WGEW are available (D. J. Breckenfeld, Soil survey of Walnut Gulch Experimental Watershed, Arizona: Adminis-

[1]Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, Arizona, USA.

[2]Department of Renewable Resources, University of Wyoming, Laramie, Wyoming, USA.

0043-1397/08/2006WR005702$09.00

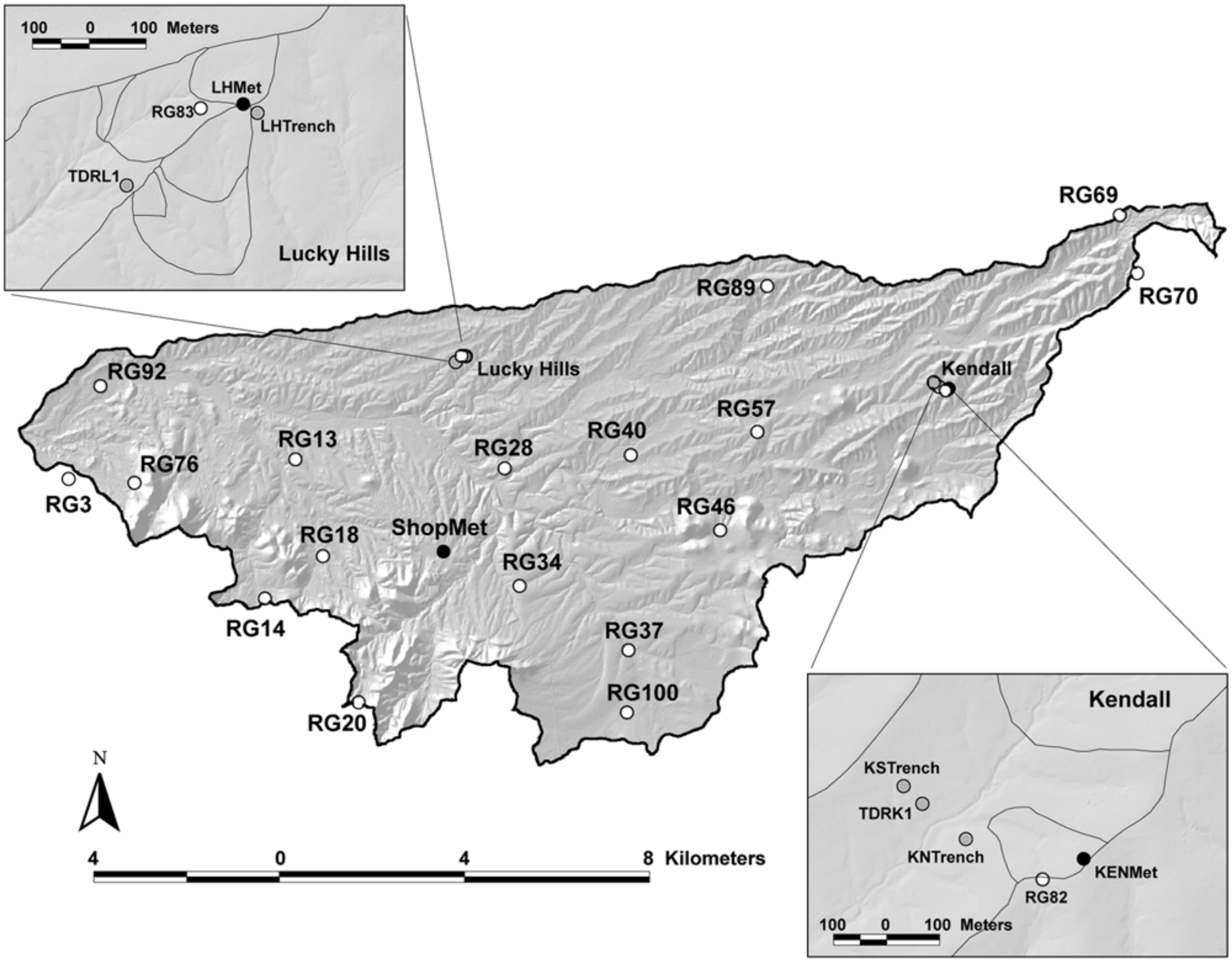

Figure 1. Meteorological and soil hydrology installations located at WGEW. AWSs are located at LHMet (31°44′8″N, 110°03′08″W), KENMet (31°44′11″N, 109°56′31″W), and ShopMet (31°42′20″N, 110°03′27″W). Manual TDR profile soil moisture is located at LHTrench, KNTrench, and KSTrench. Automated TDR is located at TDRL1 and TDRK1. Rain gauges with colocated soil moisture and soil temperature are denoted by RG numbers, four of which also have soil surface temperature.

trative report of the National Cooperative Soil Survey, unpublished manuscript, 131 pp., 1994).

[5] The AWSs at LH and KEN, LHMet and KENMet respectively, and three soil profile trenches, LHTrench, KNTrench and KSTrench were established in 1990 during the Monsoon'90 Multidisciplinary Experiment [*Kustas and Goodrich*, 1994]. The primary objective of Monsoon'90 was to determine the feasibility of combining remotely sensed data with water and energy balance models to estimate fluxes on semiarid rangelands. In 2003, two different soil profile trench sites were installed at LH (TDRL1) and KEN (TDRK1) as part of the NASA-JPL MOSS research project [*Moghaddam et al.*, 2003]. The objective of MOSS was to evaluate prototype multifrequency ground penetrating radar for estimation of soil moisture at depth from a space-based platform.

[6] Since 2002, near surface soil moisture and temperature probes have been colocated with WGEW rain gauges at 19 locations. The sites were chosen to represent the diversity of soils [*Heilman et al.*, 2008] and for the spatial distribution of the locations across the watershed. They were installed as part of the joint Agricultural Research Service (ARS)–NASA Soil Moisture Experiments in 2004 (SMEX04) project [*Jackson et al.*, 2008]. The main objective of SMEX04 was the validation of remotely sensed data from aircraft and spaceborne microwave sensors and the associated mapping of distributed soil moisture. The third AWS (ShopMet) is located at the WGEW field office in Tombstone, Arizona, and has been in operation since 1995. Because of the disturbed and compacted nature of the ground, no soil hydrology is measured at this site.

[7] All locations, with the exception of the Monsoon'90 soil profile trenches that were in operation from 1990 to 1998, are equipped with Campbell Scientific, Inc (CSI) data loggers to sample and record data. Use of trade names in this report is for information purposes only and does not constitute an endorsement by the USDA-ARS.

[8] Because installation of soil hydrology instrumentation poses more challenges than, for instance, a standard weather station, an overview of installation techniques is presented. The installation process for each soil profile trench was similar. A trench was excavated by hand or backhoe. A small horizontal cavity, large enough to accept the soil

Table 1. WGEW Meteorological and Soil Hydrology Network Locations, Surface Cover, Soil Series, Texture and 5 cm Bulk Density

Location	UTM NAD83 East	UTM NAD83 North	Elevation	Cover	Soil Series and Texture Class	Bulk Density 5 cm, g cm^{-3}
LHMet	589773	3512434	1370	shrub	Luckyhills McNeal complex very gravelly sandy loam	1.64
KENMet	600231	3511719	1531	grass	Elgin-Stronghold complex very gravelly fine sandy loam	1.61
ShopMet	589310	3508200	1406	na[a]	disturbed	na
LHTrench	589798	3512418	1368	shrub	Luckyhills McNeal complex very gravelly sandy loam	1.61
KNTrench	600009	3511756	1515	grass	Elgin-Stronghold complex very gravelly fine sandy loam	1.55
KSTrench	599892	3511855	1511	grass	Elgin-Stronghold complex very gravelly fine sandy loam	1.50
TDRL1	589567	3512290	1366	shrub	Luckyhills McNeal complex very gravelly sandy loam	1.65
TDRK1	599927	3511822	1504	grass	Elgin-Stronghold complex very gravelly fine sandy loam	1.77
RG 3	581204	3509768	1246	shrub	Luckyhills McNeal complex very gravelly sandy loam	1.81
RG 13	586110	3510185	1334	shrub	Monterosa very gravelly fine sandy loam	1.61
RG 14	585442	3507187	1390	shrub	Chiricahua very gravelly clay loam	1.81
RG 18	586710	3508098	1365	shrub	Shiefflin very stony loamy sand	1.59
RG 20	587480	3504939	1525	shrub	Mabray rock outcrop complex cobbly clay loam	1.63
RG 28	590624	3509990	1369	shrub	Graham cobbly clay loam	1.69
RG 34	590946	3507458	1420	shrub	Sutherland very gravelly fine sandy loam	1.52
RG 37	593303	3506068	1404	shrub	Monterosa very gravelly fine sandy loam	1.71
RG 40	593360	3510286	1390	shrub	Baboquivari-Combate complex sandy loam	1.81
RG 46[b,c]	595289	3508655	1445	grass	Clay loam	1.65
RG 57	596089	3510781	1456	grass	Tombstone very gravelly fine sandy loam	1.67
RG 69[c]	603916	3515463	1638	grass	Blacktail gravelly sandy loam	2.02
RG 70	604288	3514207	1630	grass	Woodcutter gravelly sandy loam	1.80
RG 76	582624	3509679	1311	shrub	Lampshire rock outcrop complex very cobbly loam	1.79
RG 82[b]	600154	3511680	1530	grass	Elgin-Stronghold complex very gravelly fine sandy loam	1.61
RG 83[b]	589697	3512426	1370	shrub	Luckyhills McNeal complex very gravelly sandy loam	1.65
RG 89	596308	3513931	1491	grass	Stronghold-Bernardino complex very gravelly loam	1.82
RG 92[c]	581888	3511774	1244	grass	McAllister Stronghold complex sandy clay loam	1.59
RG 100[c]	593266	3504720	1418	shrub	Mabray rock outcrop complex cobbly loam	1.91

[a]Na means not applicable.
[b]This rain gauge is equipped with additional soil moisture sensors at 15 and 30 cm.
[c]This rain gauge is equipped with an IRT for soil surface temperature.

moisture probe body, was created in the exposed trench face at the designated installation depth. Probes were inserted horizontally into this cavity, by pushing the probe tines into the soil at the recessed end of the cavity, until the probe head was within the cavity. The cavity was repacked with the soil that had been removed. Probe lead wires were run vertically down the trench face, across the bottom of the trench and up the other side, thus preventing preferential flow paths to probe head and tines. Multiple profiles were installed in the same trench, or in side by side trenches, under representative soil surface cover. Although every attempt was made to assure good contact between soil and tines, it was impossible to know the extent of soil cracking around the tines at time of installation. Installation of soil temperature thermocouples in the same trenches was identical. Installation in the near surface, such as at the rain gauges and AWSs, of soil moisture, temperature and heat flux sensors was similar, but these shallow trenches were manually excavated and the soil surface was stabilized when installing very near to the surface, 1 and 2 cm. Proper installation is the initial step in data quality control.

2.2. Meteorological and Soil Hydrology Elements

[9] The specific locations of LHMet and KENMet have remained unchanged since established in 1990 and that of ShopMet has remained the same since established in 1995. The meteorological elements common to all AWSs are air temperature, relative humidity, wind speed, wind direction, barometric pressure, solar radiation and photosynthetically active radiation. Net radiation is measured at LHMet and KENMet. A single sensor is used to measure each variable at each AWS. Barometric pressure is sampled once and output at the output time step; all other sensors are sampled every 10 s and averaged at the output time step, either 20 or 60 min. Manufacturer supplied calibration or conversion factors are employed to report output in standard units. Summary information on the meteorological variables and sensors of the AWSs are given in Table 2.

[10] Soil hydrology properties have been measured at LHMet and KENMet, soil profile trenches LHTrench, KNTrench, KSTrench and TDRL1 and TDRK1, and colocated with recording rain gauges across WGEW. Soil hydrology measurements are soil moisture, soil temperature, soil heat flux and soil surface temperature. From 1990 to May 1998, soil moisture was measured by manual readings of time domain reflectometry (TDR) at LHTrench, KNTrench and KSTrench [*Hymer et al.*, 2000]. Soil moisture was measured on an occasional basis throughout the soil profile to 50 cm. On each sampling occasion, measurements for each depth (5, 10, 15, 20, 30 and 50 cm) at multiple profiles were averaged to provide a location average for each depth. All four soil hydrology variables have been measured at LHMet and KENMet. From 1996 to 2001 soil moisture was measured by electric resistance sensors at 5 cm and from 2001 to present by capacitance sensors at 5 and 15 cm. Samples were taken every 20 min and the average of three sensor readings at each depth is reported. Three repetitions of soil temperature, at 2 and 6 cm, and heat flux at 8 cm, sampled at 10 s intervals and averaged every 20 min, have been measured from 1996 to present and the average reported for each depth; since 2001 three repetitions of soil temperature at 1 cm have been similarly sampled and temporally averaged and the depth average reported. Soil surface temperature has been measured since 2004 with a

Table 2. WGEW Meteorological Variables and Sensors: Summary Information

Variable[a]	Units	Sensor	Accuracy[b]	Height, m	Output Time, min	Output Type	Period
			LHMet and KENMet				
Tair	deg C	CSI T107	±0.5°C	2.0	60	average	1990–1993
		HMP35C	±0.4°C	2.0	60	average	1993–1996
					20	average	1996–2001
		HMP45C	±0.4°C	2.0	20	average	2001–2006
RH	%	CSI 207	±5%	2.0	60	average	1990–1993
		HMP35C	±0.3%	2.0	60	average	1993–1996
					20	average	1996–2001
		HMP45C	±0.3%	2.0	20	average	2001–2006
Ws	$m\ s^{-1}$	RM Young 3001	±0.5 $m\ s^{-1}$	3.5	60	average	1990–1996
				3.5	20	average	1996–2006[c]
Wd	deg	RM Young 3001	±5 deg.	3.5	60	average	1990–1996
				3.5	20	average	1996–2006[c]
Bar	mb	CS105	±6 mb	1.7	20	sample	2001–2006
Sol	$W\ m^{-2}$	Li-Cor 200	±3%	3.5	60	average	1990–1996
				3.5	20	average	1996–2006
PAR	$mmol\ s^{-1}\ m^{-2}$	Li-Cor 190	±3%	3.2	60	average	1993–1996
				3.2	20	average	1996–2006
Rnet	$W\ m^{-2}$	REBS Q6	<10%	3.0	60	average	1990–1996
		REBS Q7	<10%	3.0	20	average	1996–2004
			ShopMet				
Tair	deg C	HMP35C	±0.4°C	2.0	60	average	1995–1996
		HMP45C	±0.4°C	2.0	20	average	2001–2006
RH	%	HMP35C	±0.3%	2.0	60	average	1995–1996
		HMP45C	±0.3%	2.0	20	average	2001–2006
Ws	$m\ s^{-1}$	RM Young 3001	±0.5 $m\ s^{-1}$	3.5	60	average	1995–1996
				3.5	20	average	1996–2006
Wd	deg	RM Young 3001	±5°	3.5	60	average	1995–1996
				3.5	20	average	1996–2006
Bar	mb	Vaisala PT427	±6 mb	1.7	60	sample	1995–1996
					20		1996–1999
		CS105	±6 mb	1.7	20	sample	2001–2006
Sol	$W\ m^{-2}$	Li-Cor 200	±3%	3.5	60	average	1995–1996
				3.5	20	average	1996–2006
PAR	$mmol\ s^{-1}\ m^{-2}$	Li-Cor 190	±3%	3.2	20	average	2001–2006

[a]Abbreviations: Tair, air temperature; RH, relative humidity; Ws, wind speed; Wd, wind direction; Bar, barometric pressure; Sol, solar radiation; PAR, photosynthetically active radiation; Rnet, net radiation.
[b]Accuracies are determined from manufacturers' specifications, field calibrations or estimates from other users.
[c]Ws and Wd at LHMet are available from 2001 to 2006.

single sensor and reported as a 20 min sample. Soil moisture and temperature have been measured through the soil profile to 200 cm at TDRL1 and TDRK1 since 2003 and 2004, respectively. A CSI TDR100 unit processes signals at a 20-min sampling frequency. At TDRL1 there are seven TDR probes installed in a bare surface profile and another seven in a shrub cover profile each with sensor depths of 5, 15, 30, 50, 75, 100 and 200 cm. At TDRK1 3 profiles under grass cover were established with 7 sensors in profile at the same depths as TDRL1. Averages at each depth at each location are reported for each variable. Soil moisture and soil temperature have been measured with a single sensor at 19 rain gauges across the watershed since 2002; originally sampled and reported every 30 min, but at 20 min intervals since 2003. Soil surface temperature is also measured at four of the 19 rain gauges by a single sample every 20 min. Summary information on the soil hydrology variables and sensors is given in Table 3.

3. Data Quality

[11] All meteorological sensors were installed and are maintained according to manufacturer's specifications and use manufacturer supplied calibrations when appropriate. Soil hydrology probes were also installed per manufacturer's specifications and calibrations when available. TDR soil moisture probes installed in 1990 were calibrated to site specific soils and the signal converted to volumetric water content. Electric resistance sensors at AWSs from 1996 to 2001 were calibrated to TDR installed at nearby sites [*Amer et al.*, 1994; *Hymer et al.*, 2000]. Delta T Theta probes installed at AWSs in 2001 make use of a combination of the manufacturers generic mineral calibration to convert to volumetric water content and calibration to gravimetric samples collected on site. Stevens Hydra probes installed at rain gauges use factory sand calibration except for rain gauge 46 that uses the factory clay calibration. TDR installed in trenches in 2003/2004 were calibrated to site specific soils and the signal converted to volumetric water content.

[12] The initial data stream from field sites may contain missing values for any property because the station was not in operation intentionally or accidentally, the sensor was not deployed at that time, or there was data collection, communication or computer failure. Data determined to be collected during periods when a sensor was known to be inoperable

Table 3. WGEW Soil Hydrology Variables and Sensors: Summary Information

Soil Variable	Units	Sensor	Accuracy	Depth, cm	Output Time, min	Output Type	Period
				LHMet and KENMet			
Moisture	%	electric resistance	±5%	5	20	average	1996–2001
		delta T theta probe	±5%	5, 15	20	average	2001–2006
Temperature	deg C	thermocouple	±0.2°C	2, 6	20	average	1996–2006
				1	20	average	2001–2006
		apogee IRT	±0.5°C	surface	20	sample	2004–2006
Heat flux	W m^{-2}	REBS	±5%	8	20	average	1996–2006
				LHTrench, KNTrench, and KSTrench			
Moisture	%	TDR	±5%	5, 10, 15, 20, 30, 50	various (days)	average	1990–1998
				TDRL1			
Moisture	%	TDR	±5%	5, 15, 30, 50, 75, 100, 200	20	average	2003–2006
Temperature	deg C	thermocouple	±0.2°C	5, 15, 30, 50, 75, 100, 200	20	average	2003–2006
				TDRK1			
Moisture	%	TDR	±5%	5, 15, 30, 50, 75, 100, 200	20	average	2004–2006
Temperature	deg C	thermocouple	±0.2°C	5, 15, 30, 50, 75, 100, 200	20	average	2004–2006
				Rain Gauges[a]			
Moisture	%	Stevens Hydra probe	±5%	5, 15, 30	30	sample	2002
				5, 15, 30	20	sample	2003–2006
Temperature	deg C	Stevens Hydra probe	±5%	5, 15, 30	30	sample	2002
				5, 15, 30	20	sample	2003–2006
		apogee IRT	±0.5°C	surface	20	sample	2004–2006

[a]Refer to Table 1 for rain gauge locations with 15 and 30 cm soil moisture and soil surface temperature.

(e.g., vandalism, animal or natural interference) were coded with missing values. Incoming data, after transformation from measured value to final units, if applicable, are screened by automated and visual graphic processes for outliers beyond acceptable limits. Outliers that are physically impossible (e.g., negative soil moisture, temperature above 100°C) are coded as missing. Limits imposed on meteorological values are from various sources: 40 years of NWS Cooperative Observer station at WGEW field office for air temperature and relative humidity; sensor range from manufacturers manuals for wind speed, wind direction and barometric pressure; estimated limits for solar, photosynthetically active and net radiation from the Arizona Meteorological Network (http://cals.arizona.edu/azmet/azdata.htm) and California Irrigation Management Information System (http://www.cimis.water.ca.gov/cimis/dataQc.jsp); and model output for solar, photosynthetically active and net radiation from procedures outlined by *Meek and Hatfield* [1994]. The limit of maximum soil moisture is estimated field capacity based on soil classification texture [*Rawls et al.*, 1982] and that of maximum soil surface temperature is 70°C. The acceptable range of below-surface soil temperature is between 60° and −10°C and that of soil heat flux between 60 and −150 W m^{-2}. Instrument data that fall outside the limits are kept in the database. Data that fall outside the limits are not flagged, but counted for informational purposes. Soil heat flux exceeded the maximum in <0.02% of valid observations and never exceeded the minimum. Soil moisture rarely exceeded field capacity at only 2 of 19 rain gauge sites (<0.03%) and at none of the soil profile sites nor AWSs. Similarly, soil temperature rarely exceeded the maximum at only 4 of 19 rain gauges (<0.04%) and not elsewhere. Soil temperature exceeded the minimum only at LHMet (<0.01%). Similarly, soil surface temperature exceeded the minimum at LHMet and 3 of 4 rain gauges (<0.01%), but never the maximum.

[13] Meteorological variables that never exceeded limits are wind speed, wind direction and barometric pressure. Relative humidity was detected over range (<0.01%) only at KENMet. Air temperature exceeded maximum and minimum limits at KENMet (<0.01% and <0.02%), LHMet (<0.05% and <0.04%) and ShopMet (<0.12% and <0.14%). Net radiation exceeded maximum estimates at KENMet (<0.20%) and LHMet (<0.06%). Photosynthetically active radiation exceeded estimated maximums <0.06%, <0.12% and <0.03% at KENMet, LHMet and ShopMet, respectively. Solar radiation exceeded maximum estimates 1.65%, 2.30% and 4.70% at KENMet, LHMet and ShopMet, respectively.

[14] A 38 year (1963–2000) maximum and minimum daily temperature for each day of the year was determined from observations collected at the NWS cooperative observer station located at the WGEW field office in Tombstone, Arizona, and compared to similar values determined for LHMet and KENMet for the period of record (Figure 2). A sinusoidal regression model was fit to the WGEW field office data (Figure 2). The lowest low value, −16°C day 342 and nearby days, was a valid observation from the field office, as are the highest high values (days 21, 188 and 305). The low value on day 192 observed at KENMet would exceed the temperature minimum limit imposed by the model and be counted in the statistics of out of range values, but would not be eliminated from the database.

[15] There is a near-continuous record of soil moisture at LH and KEN; however, the sampling method, sampling frequency, profile depths and exact locations have varied over the 17 year period. For example, at LHMet and

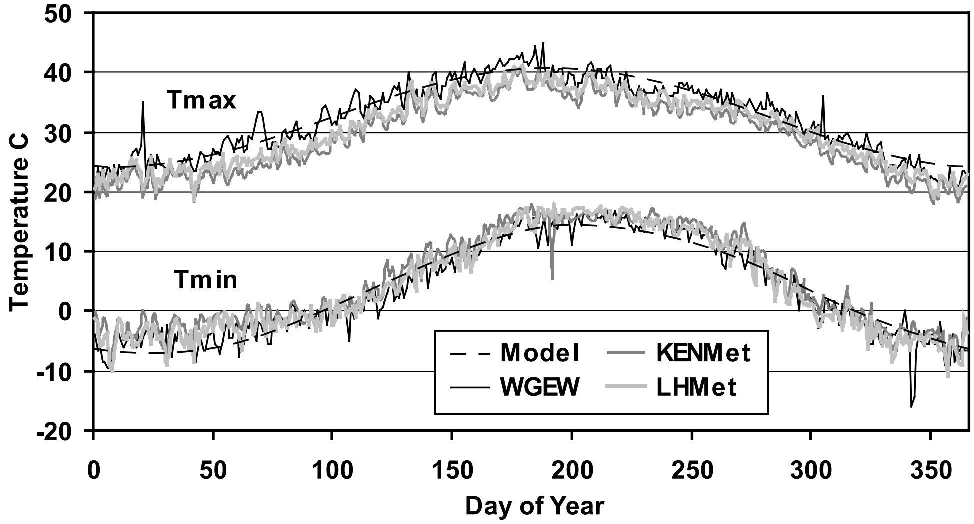

Figure 2. Maximum and minimum daily observed temperatures (T_{max} and T_{min}) for each day of the year from nearly 17 years (1990–2006) at LHMet and KENMet and 38 years (1963–2000) at the WGEW field office and a sinusoidal regression model (Model) fit to the WGEW field office data. The lowest lows near day 330 and the highest highs near days 20, 180, and 300 are all valid observations from the field office. The daily low deviation recorded at KENMet near day 180 would be flagged and counted as exceeding the temperature minimum limit.

KENMet, soil moisture has been measured at 5 cm since mid-1996. However, the sensing technology was changed for the 5 cm sensor in mid-2001 from an electric resistance sensor to a capacitance sensor, the Delta T Theta probe. For the period 1996 to 2006 at LHMet and KENMet, sensor daily maximum soil moisture (%) in response to daily precipitation (mm) was not necessarily biased by the change in sensor (Figures 3a and 3b). Variations in sensor response and data trends that may be induced by changes in instrument technology are acknowledged and have been discussed by SWRC as an issue for field data collection [*Paige and Keefer*, 2008]. Users of these data should be aware of this possible instrument effect; hence the list of sensor changes is given in Tables 2 and 3.

4. Data Availability

[16] The WGEW meteorological and soil hydrology data presented in Tables 2 and 3 are available at http://www.tucson.ars.ag.gov/dap maintained by the USDA Agricultural Research Service, SWRC. More complete descriptions of the data, data formats and metadata associated with the data can be found at the same site.

5. Examples of Data Use

[17] The simultaneous measurements of meteorological and soil hydrology properties are particularly valuable for ecohydrological studies because they are temporally extensive covering multiple seasons and years, as well as spatially distributed in a heterogeneous watershed. These characteristics of the data have spawned research specifically focused on the hydrologic dynamics of shrub and grass ecosystems. *Scott et al.* [2000] made an assessment of the soil moisture recharge under shrub and grass cover based on 8 years of root zone soil moisture measurements (Table 3). They reported that the deeper-rooted shrubs retained the ability to obtain moisture from the near surface, thus allowing competition with the shallower-rooted grasses. M. S. Moran et al. (Partitioning evapotranspiration in semiarid grassland and shrubland ecosystems using time series of soil surface temperature, submitted to *Journal of Agricultural and Forest Meteorology*, 2007) exploited the long-term, high temporal frequency IRT measurements (Tables 2 and 3) to determine the differences in transpiration from shrub- and grass-dominated ecosystems and better understand the hydrologic impact of regional woody plant encroachment. C. D. Holifield Collins et al. (A remote sensing approach for estimating distributed daytime net carbon dioxide flux in semiarid grasslands, submitted to *Water Resources Research*, 2006) used a 13 year record of meteorological data (Table 2) in conjunction with satellite imagery to map daytime net CO_2 flux from WGEW grasslands. *Emmerich and Verdugo* [2008] combined the soil heat flux measurements made in multiple locations at LHMet and KENMet (Table 3) to characterize the ecosystem flux that was not represented by only a single heat flux plate under one cover and management condition.

[18] The WGEW meteorological data, in combination with the extensive precipitation data [*Goodrich et al.*, 2008], have been the forcing variables used for several process model simulations [e.g., *Hymer et al.*, 2000; *Das et al.*, 2008]. Further, these models have been coupled with the WGEW remote sensing and GIS database [*Santanello et al.*, 2007; C. D. Peters-Lidard et al., The role of precipitation uncertainty for soil property estimation using soil moisture retrievals in a semiarid environment, submitted to *Water Resources Research*, 2007]. Conversely, satellite imagery has been combined with optical and microwave radiative transfer models to retrieve meteorological and surface conditions at a point in time [*Houborg*

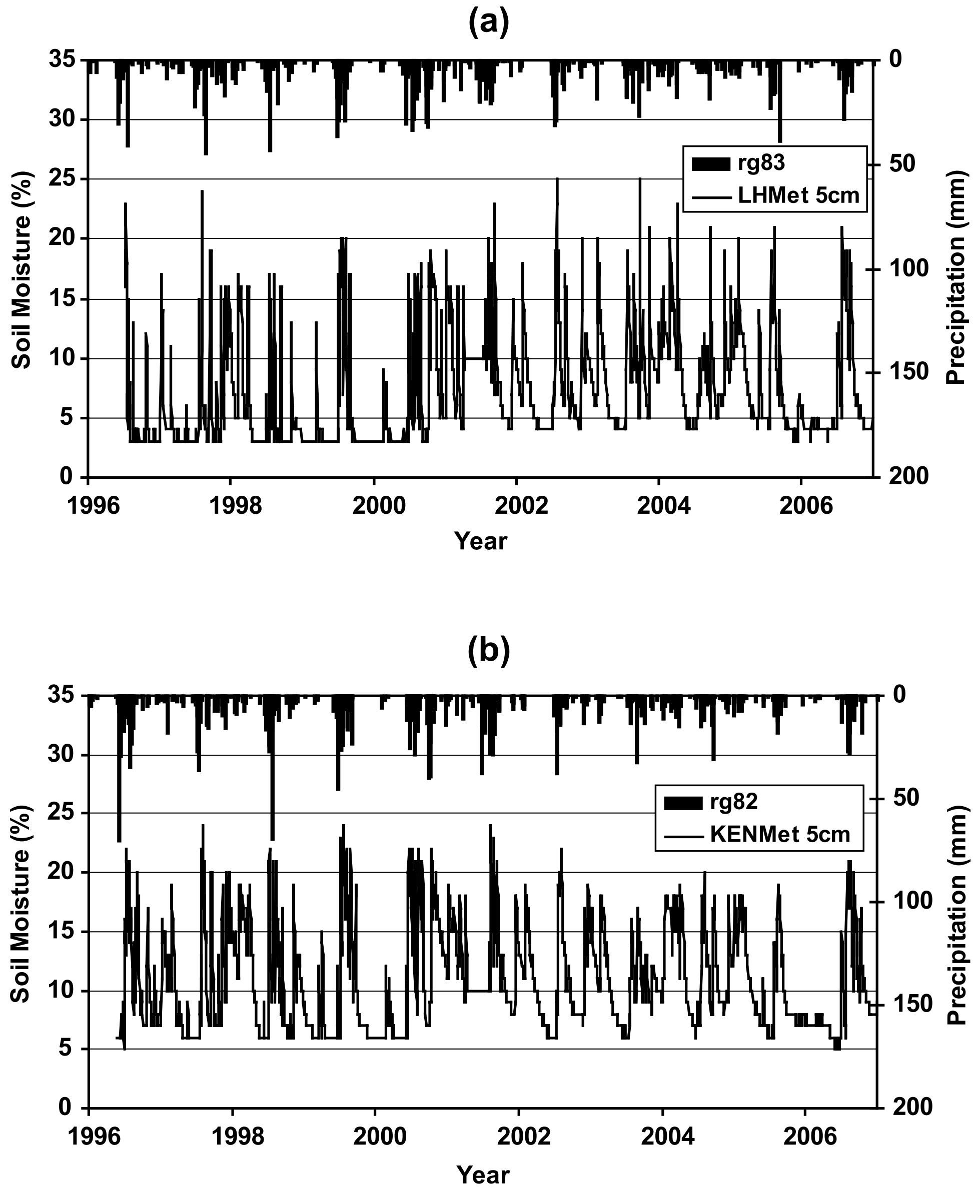

Figure 3. Daily maximum 5 cm soil moisture (% by volume) and daily precipitation (mm) 1996–2006 with change in sensing technology in mid-2001 from electric resistance to capacitance soil moisture sensor at (a) LHMet and (b) KENMet.

et al., 2007; *Rahman et al.*, 2008]. In all cases, the modeling results were validated with observations from the meteorological and soil hydrology networks described in section 2.

6. Summary

[19] The SWRC WGEW meteorological and soil hydrology database offers the opportunity to study semiarid ecosystem dynamics at the watershed spatial scale. The combination of these data with the dense rain gauge and flume network and other ground-based measurements of vegetation, soil and erosion conditions will continue to support ecohydrological studies and hydrologic and erosion modeling. In addition, these data will provide surface observations to assist in improvements to land, aircraft and satellite remote sensors and model validation SWRC is committed to maintaining the continuity of these data and providing these to the scientific community.

[20] **Acknowledgments.** Special thanks to SWRC staff, located in Tombstone, Arizona, for maintaining the WGEW NWS Cooperative Observer site for many years and to the many SWRC employees and students who assisted in soil moisture data collection at WGEW. The authors would like to thank Lainie Levick for Figure 1. The original automated weather stations at Lucky Hills and Kendall and TDR trenches were funded by Monsoon'90. Stevens Hydra probes and IRTs at rain gauge sites were funded by ARS-NASA SMEX04, and current TDR sites were funded by NASA-JPL MOSS project.

References

Amer, S. A., T. O. Keefer, M. A. Weltz, D. C. Goodrich, and L. B. Bach (1994), Soil moisture sensors for continuous monitoring, *Water Resour. Bull.*, *30*(1), 69–83.

Cosh, M. H., T. J. Jackson, M. S. Moran, and R. Bindlish (2008), Temporal persistence and stability of surface soil moisture in a semi-arid watershed, *Remote Sens. Environ.*, *112*, 304–313.

Das, N. N., B. P. Mohanty, M. H. Cosh, and T. J. Jackson (2008), Modeling and assimilation of root zone soil moisture using remote sensing observations in Walnut Gulch Watershed during SMEX04, *Remote Sens. Environ.*, *112*, 415–429.

Emmerich, W. E., and C. L. Verdugo (2008), Precipitation thresholds for CO_2 uptake in grass and shrub plant communities on Walnut Gulch Experimental Watershed, *Water Resour. Res.*, *44*, W05S16, doi:10.1029/2006WR005690.

Gebremichael, M., and E. R. Vivoni (2008), Spatial sampling uncertainty in SMEX04 soil moisture fields: A data-based resampling experiment, *Remote Sens. Environ.*, *112*, 326–336.

Goodrich, D. C., T. O. Keefer, C. L. Unkrich, M. H. Nichols, H. B. Osborn, J. J. Stone, and J. R. Smith (2008), Long-term precipitation database, Walnut Gulch Experimental Watershed, Arizona, USA, *Water Resour. Res.*, doi:10.1029/2006WR005782, in press.

Heilman, P., M. H. Nichols, D. C. Goodrich, S. N. Miller, and D. P. Guertin (2008), GIS database, Walnut Gulch Experimental Watershed, Arizona, USA, *Water Resour. Res.*, doi:10.1029/2006WR005777, in press.

Houborg, R., H. Soegaard, W. E. Emmerich, and M. S. Moran (2007), Inferences of all-sky solar irradiance using Terra and Aqua MODIS satellite data, *Int. J. Remote Sens.*, *28*, 4509–4535.

Hymer, D. C., M. S. Moran, and T. O. Keefer (2000), Soil water evaluation using a hydrologic model and calibrated sensor network, *Soil Sci. Soc. Am. J.*, *64*, 319–326.

Jackson, T. J., M. S. Moran, and P. E. O'Neill (2008), Introduction to Soil Moisture Experiments 2004 (SMEX04) special issue, *Remote Sens. Environ.*, *112*, 301–303.

King, D. M., S. M. Skirvin, C. D. Holifield Collins, M. S. Moran, S. H. Biedenbender, M. R. Kidwell, M. A. Weltz, and A. Diaz-Gutierrez (2008), Assessing vegetation change temporally and spatially in southeastern Arizona, *Water Resour. Res.*, doi:10.1029/2006WR005850, in press.

Kustas, W. P., and D. C. Goodrich (1994), Preface, *Water Resour. Res.*, *30*(5), 1211–1225.

Meek, D. W., and J. L. Hatfield (1994), Data quality checking for single station meteorological databases, *Agric. For. Meteorol.*, *69*, 85–109.

Moghaddam, M., et al. (2003), Microwave Observatory of Subcanopy and Subsurface (MOSS): A low-frequency radar for global deep soil moisture measurements, paper presented at International Geoscience and Remote Sensing Symposium, Geosci. and Remote Sens. Soc., Toulouse, France.

Nouvellon, Y., M. S. Moran, D. Lo Seen, R. B. Bryant, W. Ni, A. Begue, A. G. Chehbouni, W. E. Emmerich, P. Heilman, and J. Qi (2001), Coupling a grassland ecosystem model with Landsat imagery for a 10-year simulation of carbon and water budgets, *Remote Sens. Environ.*, *78*, 131–149.

Paige, G. B., and T. O. Keefer (2008), Field application performance of multiple soil moisture sensors, *J. Am. Water Resour. Assoc.*, in press.

Rahman, M. M., M. S. Moran, D. P. Thoma, R. Bryant, C. D. Holifield Collins, S. Skirvin, T. Jackson, B. J. Orr, and M. Tischler (2008), Mapping surface roughness and soil moisture using radar imagery without ancillary data, *Remote Sens. Environ.*, *112*, 391–402.

Rawls, W. J., D. L. Brakensiek, and K. E. Saxton (1982), Estimation of soil water properties, *Trans. ASAE*, *22*(5), 1316–1320.

Renard, K. G., M. H. Nichols, D. A. Woolhiser, and H. B. Osborn (2008), A brief background on the USDA Agricultural Research Service Walnut Gulch Experimental Watershed, *Water Resour. Res.*, doi:10.1029/2006WR005691, in press.

Santanello, J. A., Jr., C. D. Peters-Lidard, M. E. Garcia, D. M. Mocko, M. A. Tischler, M. S. Moran, and D. P. Thoma (2007), Using remotely-sensed estimates of soil moisture to infer soil texture and hydraulic properties across a semi-arid watershed, *Remote Sens. Environ.*, *110*, 79–97.

Scott, R. L., W. J. Shuttleworth, T. O. Keefer, and A. W. Warrick (2000), Modeling multiyear observations of soil moisture recharge in the semi-arid American Southwest, *Water Resour. Res.*, *36*, 2233–2247.

Skirvin, S., M. Kidwell, S. Biedenbender, J. P. Henley, D. King, C. Holifield Collins, S. Moran, and M. Weltz (2008), Vegetation data, Walnut Gulch Experimental Watershed, Arizona, USA, *Water Resour. Res.*, doi:10.1029/2006WR005724, in press.

Thoma, D., et al. (2008), Appropriate scale of soil moisture retrieval from high-resolution radar imagery for bare and minimally vegetated soils, *Remote Sens. Environ.*, *112*, 403–414.

T. O. Keefer and M. S. Moran, Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, AZ 85719, USA. (tim.keefer@ars.usda.gov)

G. B. Paige, Department of Renewable Resources, University of Wyoming, Laramie, WY 82071, USA.