Abstract
Knowledge of weather, particularly precipitation, is fundamental to interpreting watershed and hydrologic processes. The long-term weather record in the Goodwater Creek Experimental Watershed (GCEW) complements hydrologic and water quality data in the region. The GCEW also is the core of the Central Mississippi River Basin (CMRB) node of the Long-Term Agroecosystem Research network. Our objectives are to (i) describe the climatological context of the GCEW and CMRB settings, (ii) document instrumentation and the data collection, quality assurance, and reduction processes; (iii) provide examples of the data obtained and descriptive statistics; and (iv) document the availability of and access methods to obtain the data from the web-based data access portal at http://www.nrrig.mwa.ars.usda.gov/stewards/stewards.html. These objectives support an overall goal to make these long-term data available to the public for use in further analyses and modeling in support of research and public policy on watershed management.

Climatological Description
The region's climate is typed as continental and exhibits strong seasonality (U.S. Weather Bureau, 1959). The absence of topographic barriers in any direction allows air masses to cross the region in both winter and summer. Winter weather is dominated by a succession of cold and dry arctic air masses from...
the northern Great Plains of the United States and Canada. If these arctic air masses displace relatively humid air, snow or rain results. In summer, moist and warm air masses from the Gulf of Mexico bring rain by both fronts and convective processes. Occasionally, stagnant high pressure areas cause extended droughts. In the spring and fall, competing fast-moving fronts of contrasting air masses often cause abrupt changes in temperature and precipitation. Abrupt changes can also occur during winter and summer, despite the strong seasonality. Periods of warmer weather (importantly, above-freezing temperatures) occur frequently during winter, meaning that it is quite rare to have continuous snow or ice cover for longer than a month. Similarly, dry and cool weather occasionally interrupts the usual hot and humid summer.

**Instrumentation**

Instruments installed during establishment of the GCEW consisted of weighing recording rain gauges (1969), chart recording hygrothermographs (1971), and manual max–min thermometers (1971). Installation and data collection procedures followed standard field practice for weather instrumentation (Brakensiek et al., 1979). By the 1990s, field-capable electronic methods had been added. In the case of the rain gauges, the instruments themselves were modified. The hygrothermograph and max–min thermometer were replaced by other instruments, which then served as the GCEW standard.

**Rain Gauge Network**

Weighing, recording rain gauges were installed in 1969 in a network that reached a maximum of 39 gauges across the 189-km² Young’s Creek watershed, within which the GCEW is nested. The USGS station at Young’s Creek was originally considered part of the nested watershed design. However, after the USGS decommissioned Young’s Creek on 1 Oct. 1969 (temporarily in service 18 July 1980–30 June 1982), the rain gauge network was reduced to include only the area in and near the GCEW. The current network stands at nine gauges in 73 km², and the current locations of the gauges are shown in Fig. 1.

Standard 20-cm weighing gauges (Universal Recording Rain Gage, 5-780-9, Belfort Instrument Co.) with daily charts were installed at each site. A subset of sites (generally three) included a second gauge with weekly charts to help resolve the timing of events. A subset (variable historically, currently all nine) of the network was winterized by removing the funnel and placing ethylene glycol in the bucket to measure the rainfall equivalent of snow; the remainder were removed or covered during the winters. These gauges are unshielded, and the data reported have not been adjusted to account for wind-dependent effects. In 1997, load cells (Model 1040 G 20KG Single Point, TEDEA-Huntleigh) were installed under the buckets of all rain gauges and interrogated using a datalogger (BDR320, Campbell Scientific) to automate the measurement at 2-min intervals. Charts were continued as a backup until confidence was developed in the automated system. For both configurations, calibration of the gauges was confirmed annually in midsummer by placing in the bucket a standard weight equivalent to 254 mm of rain. Deviations exceeding ±0.76 mm triggered adjustment. Manual clocks in the rain gauges were adjusted to Naval Observatory time in spring and fall or on malfunction. However, the data were also corrected for the time of chart start and stop to reduce clock errors. Central Daylight Time was used at times; all data have been corrected to Central Standard Time. Datalogger clocks were reset to online standard time (http://www.time.gov/); errors were generally less than a few seconds.

Currently, upgrades to the dataloggers have been implemented (CR800, Campbell Scientific) to enable remote telemetry. When fully implemented, telemetry will then enable near-real-time data collection from the rain gauge network and the weather station described below.

**Data Management and Analysis**

Under both the chart and electronic configurations, data were collected weekly. Data from charts, as accumulated depth of rain, were reduced to breakpoint values and manually entered into computer files. Gauge readings in those files or later electronic datalogger files were converted to depth, which was then inspected for periods of increase and decrease using a

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**Fig. 1. Location of the weather instruments in the Goodwater Creek Experimental Watershed. Coordinates are for the MOGCWX02 weather station.**
computer program written for the purpose. Decreases caused by evaporation were set to zero, and increases were differenced to obtain rainfall depth accumulated in the interval. Quality assurance for the rain gauge data included periodic checks with standard weights and visual cross-comparisons of the accumulated rainfall from all network gauges.

**Thiessen Area-Weighted Rainfall Calculations**

The computation of watershed-area rainfall depth is necessary if a comparison to unit-area runoff from the same watershed is required. Since establishment, area-weighted rainfall corresponding to the drained area has been calculated using the Thiessen polygon method (Thiessen and Alter, 1911). The purpose of reporting this here is not to advocate the specific method but to document what was used to derive the area-weighted rainfall, which is a derived data product in the database.

Some gauges were winterized and operated continuously and others were deployed only when the water in the buckets was safe from freezing. Further, the network evolved from the original 189 km² to the current 73-km² area, and the number of gauges changed as funding changed. Even when gauge numbers were constant, landowner permissions occasionally forced gauge locations to be changed. Thus, the table of weights for the entire period is quite complex, but it provides an area-weighted estimate of the depth of precipitation on the drainage area studied.

**Manual Weather Station**

A hygrothermograph (Belfort 5-594 with bimetallic temperature sensor, Belfort Instrument Co.) was installed in 1971 at Location MOGCWX01 (Fig. 1). With it, air temperature was recorded continuously, and daily maximum and minimum were manually read and recorded. A Class A evaporation pan was maintained at that site, with daily wind run recorded at the elevation of the pan (Belfort Totalizing Anemometer 5-349). This pan was read on non-holiday weekdays with a standard hook gauge (Belfort 5-743) in a stilling well (Belfort 5-745). On 1 Apr. 1994, all these instruments were moved to Location MOGCWX02 (Fig. 1). These instruments were decommissioned in 2004. After that time, air temperature, humidity, and wind speed were measured with the automated weather station described below.

**Automated Weather Station**

An automated weather station was installed at the MOGCWX02 location (Fig. 1), with reported data starting 1 Jan. 1993. Details of the instruments and the programmable datalogger are in the Supplemental Material, Section A. Daily maximums and minimums for both air and soil temperature and daily total for precipitation were recorded. In addition, hourly average solar radiation, air temperature, saturated and actual vapor pressure, wind speed, wind direction, soil temperature, and hourly total precipitation were recorded. Initially, all data were downloaded on a weekly basis, with annual review before storage in the GCEW database. More recently, the datalogger has been interrogated remotely by telephone, with automated daily download and storage. Diagnostic charts of the preceding 7 d can be reviewed online (http://www.ars.usda.gov/Main/docs.htm?docid=21669). The comprehensive review and uploading to the unit and permanent online database remain on an annual schedule. Versioning of the application programs and data has been implemented at the time of the annual upload. Change logs were used to document records that were added and, if applicable, records that were changed. Changes of previous version data required further documentation of the reason, operator, and how the data were changed.

**Data Management And Quality Assurance Procedures**

**Metadata in the Archival Data Portal**

While description of the STEWARDS data portal is included below, data management procedures both depend on and are fed into the metadata at the data portal level. Each data theme, or table, in STEWARDS is linked to a geographic information system layer with Federal Geospatial Data Consortium (FGDC)-compliant metadata, within which the layer entities are described. In addition, each column of the tables has a corresponding record in a methods table that describes the field, laboratory, or data transformation used for the standard operation of the instruments.

**Metadata in the Weather Data Tables**

Data management for the weather station data was done with the goal of a complete daily data record for the entire period of record, which was required to run process-level models. If gaps were left in the data, modelers would need to use their own methods, by interpolating or substituting data from other sources, which may result in different data and model results. However, local researchers, who also run such models, have identified replacement values and constructed a complete time series of best estimates. These data have been provided in the data access portal, as documented below, for use by researchers who need weather data.

**Development of Replacement Values, Exceptions, and Flags**

Original raw data were retained in hourly and daily tables. For any measurement, data determined to be in error were supplemented by an additional column holding estimates by recalibration, correction, or replacement by best other source. A third column was obtained by overlaying the replacement data where it existed and retaining the raw data elsewhere. Thus, complete time series were provided, but data provenance was maintained. Each record with a datum having a replacement in the supplemental column had an ordinal flag placed in a fourth column, which was keyed to a table of exceptions that documented the action. For each action, the exception table included fields for period and affected sensors, a narrative of the action, including the equations and source data, and links to computations and visualizations of the symptoms and action if applicable. Currently, the exception table lists 46 actions in the period 1993 to 2012. These tables of exceptions were supplemental to the usual station notes.
Nearby Weather Data Resources

Daily and hourly historical data from nearby sites were available in two separate networks, documented in Supplemental Fig. S1. Daily data were available from the NOAA National Climatic Data Center’s Climate Data Online web site. Sites relevant to the GCEW and the Central Mississippi River Basin LTAR and the web links to access them are shown in Supplemental Table S2. Similarly, the University of Missouri’s Agricultural Weather Network had equipment nominally equivalent to the GCEW automated weather station, and the relevant sites and web link are listed in Supplemental Table S3.

Specific Retrospective Analyses

Two extensive retrospective Quality Assurance/Quality Control projects were completed on the weather data. One was necessitated after a cross-correlation analysis suggested that the solar radiation sensor had degraded. The other was done in response to a request for a consistent 40-yr temperature series that bridged a sensor/site change during the period of record (Supplemental Material, Section C).

Comparisons with Long-Term Normal Weather Data

Long-term (1971–2010) temperatures from the GCEW weather station and rainfall from the rain gauge network were compared with equivalent data from nearby stations listed in the Supplemental Material, Section B. These comparisons built confidence in the data from GCEW and supported the use of data from these nearby stations as sources of replacement or correlative data in case of sensor failure in the GCEW station (Supplemental Material, Section D).

Long-Term Descriptive Statistics

Descriptive annual and monthly statistics for air temperature, solar radiation, and precipitation were computed for the respective periods of record. The annual average air temperature was 12.0°C, with a July average of 25.0°C and January average of −2.7°C. Trend analysis of annual average maximum air temperature (SAS PROC AUTOREG, protected against autocorrelation and confirming normality of residuals) indicated a 0.0216°C yr⁻¹ increase, with approximate pr > |β| = 0.0387. Interestingly, the same trend analysis done by month produced only November as a significantly increasing monthly average maximum temperature, increasing by 0.0714°C yr⁻¹, with approximate pr > |β| = 0.0384. A similar analysis for minimum air temperature was not as conclusive, with a smaller slope (0.0159) and pr > |β| = 0.1021. Again, only 1 mo showed a significant trend, in that June’s monthly average minimum temperature had a slope of 0.0310°C yr⁻¹, with approximate pr > |β| = 0.0612.

Those monthly air temperature statistics (1971–2010) are shown in Supplemental Fig. S5. Record extreme values of January maximum daily air temperature ranged from −20.0 to 21.3°C, and similar extremes for minimum air temperature ranged from −29.5 to 11.5°C. Similar extreme values for July ranged from 18.1 to 43.7°C for maxima and from 8.2 to 28.6°C for minima. Absolute extremes during the period of record were −30.7°C on 22 Dec. 1989 and 43.7°C on 30 July 1980. Also shown in the same Supplemental Fig. S5 are the ranges of the 40-yr average monthly values, as well as the mean temperature for each month. The 40-yr monthly means for extrema were −7.3 and 1.8°C in January and 19.5 and 30.6°C in July.

The annual average of daily solar radiation for the period of record was 14.3 MJ m⁻² d⁻¹, but seasonal variations are considered more informative. Monthly solar radiation statistics (1993–2010) are shown in Supplemental Fig. S6. For solar radiation, monthly medians ranged from 6.2 MJ m⁻² d⁻¹ in December to 23.8 MJ m⁻² d⁻¹ in July. The 18-yr record daily values for each month range from a minimum of 0.33 MJ m⁻² d⁻¹ on 6 Dec. 1998 up to a maximum of 31.4 MJ m⁻² d⁻¹ on 6 June 2000. Supplemental Fig. S6 also shows the maximum and minimum of the 18 yr of monthly averages for each month.

Annual area-weighted rainfall in the GCEW for the period 1970 to 2010 (Supplemental Fig. S7) ranged from 569 mm in 1980 to 1620 mm in 2008, with a mean of 981 mm. Trend analysis of the annual total rainfall was inconclusive. The maximum monthly value for the 41-yr period of record was 482 mm in July 2008. The interquartile range and medians of the monthly rainfall data (Supplemental Fig. S8) give an indication of the seasonal patterns and variation of rainfall in the GCEW. Monthly median rainfall ranged from approximately 35 to 40 mm in December through February and from 90 to 110 mm in May through August. The median of all monthly rainfall data was 67 mm.

Availability and Access

The weather station data are available to the public through the STEWARDS (Sustaining the Earth’s Watersheds—Agricultural Research Database System) database (Steiner et al., 2008, 2009a, 2009b; Sadler et al., 2008). The web address is http://www.nrrig.mwa.ars.usda.gov/stewards/stewards.html. The upload to STEWARDS is done annually, with the goal to have data for the period of record current to within 2 yr, which is consistent with LTAR data currency expectations. The USDA-ARS has committed to maintaining STEWARDS as the permanent public access to this data store. The data themes and methods tables in STEWARDS that are relevant to the weather data are shown in Supplemental Material, Section F, as is a navigation aid to obtain data from STEWARDS.

Prior and Ongoing Research with the Data

The GCEW data set has seen relatively few uses outside of the local scientific staff and their cooperators; therefore, increasing its utility to the scientific community and the public were primary motivations for publishing the documented data set. However, some use of the weather data has been published and other research is underway. Limpert et al. (2008) examined the correlation between individual rain gauge results and NEXRAD data for specific storm events. Ponce Campos et al. (2013) examined the resilience of ecosystems to drought events at multiple locations with long-term data. The project that is underway involves analysis of data from eight locations using downscaled climate projections from seven general circulation models (J.D. Garbrecht, personal communication, 2014).
Aside from these analyses of the weather data proper, there have been a number of literature reports that used the data to drive process models, including SWAT (Bockhold et al., 2006; Ghidey et al., 2007), APEX (Mudgal et al., 2010a, 2010b, 2012; Wang et al., 2012; Senaviratne et al., 2013), HSPF (Duru et al., 1999; Hjelmfelt and Wang, 1999), CERES-Maize (Fraisse et al., 2001; Hong et al., 2004), CROPGRO-soybean (Wang et al., 2003), SIYM (Jiang et al., 2008), and RZWQM (Ghidey et al., 1999). The published literature suggests a wide variety of potential research analyses and modeling approaches enabled by GCEW weather data.

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References


