Long-term precipitation database, Walnut Gulch Experimental Watershed, Arizona, United States

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[1] An extensive precipitation database at the ~149 km^2 Walnut Gulch Experimental Watershed (WGEW) has been developed over the past 53 years with the first records starting in August 1953 and continuing to the present. The WGEW is a tributary of the San Pedro River, is located in southeastern Arizona, and surrounds the town of Tombstone. Average annual precipitation for the period of 1956–2005, as measured with six gauges, is roughly 312 mm, with approximately 60% falling during the summer monsoon. From a historical high of 95 rain gauges, a current network of 88 gauges is operational. This constitutes one of the densest rain gauge networks in the world (~0.6 gauges/km^2) for watersheds greater than 10 km^2. Through 1999, the network consisted of analog recording weighing rain gauges. In 2000, a newly designed digital gauge with telemetry was placed adjacent (~1 m) to the analog gauges. Both the analog and digital networks of gauges were in operation from 2000 to 2005 to enable a comparative analysis of the two systems. The analog data were digitized from paper charts and were stored in breakpoint format. The digital data consist of rainfall depths at 1-min intervals during periods of rainfall. All these data can be obtained in a variety of formats and were accumulated over various time intervals (daily, monthly, and annual) via a web interface at http://www.tucson.ars.ag.gov/dap/.

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1. Introduction

[2] Observation and measurement of the spatial and temporal variations of precipitation are fundamental to our understanding of watershed and hydrological processes. The U.S. Department of Agriculture, Agricultural Research Service, Southwest Watershed Research Center (SWRC) operates a precipitation gauge network as part of a more comprehensive watershed network on the Walnut Gulch Experimental Watershed (WGEW) [*Hanson*, 2001; *Osborn et al.*, 1979a; *Osborn*, 1983; *Renard et al.*, 2007]. The drainage area of the WGEW is approximately 149 km^2 and is located in southeastern Arizona. Elevation of the watershed ranges from 1220 m to 1950 m above MSL. Precipitation consists almost solely of rainfall with relatively rare instances of hail and snowfall. *Chery and Osborn* [1971] and *Chery and Kagan* [1975] provide an early summary of the precipitation facilities and data processing procedures employed at the WGEW. The present paper will draw on these summaries and update much of the information contained therein.

2. Instrumentation and Precipitation Gauge Network

[3] The analog network consisted of Belfort 0.2032 m (8 inch) unshielded weighing-recording gauges (use of trade names in this report is for information purposes only and does not constitute an endorsement by USDA-ARS). The gauges were installed so that the top edge of the gauge orifice was nominally 0.91 m (36 inches) above the ground surface. The gauges record accumulated rainfall versus time as a pen trace on a paper chart attached to the side of a rotating, clock-driven drum. The vast majority of analog gauges were fitted with clock gears and charts such that one revolution of the drum is equivalent to a 24-h period. A smaller number of gauges were set up with weekly clocks and charts, to aid in interpreting the storm event timing of the daily gauges. Several gauges were also equipped with 6-h clocks and charts to provide finer time resolution for several nested WGEW source area catchments.

[4] In the mid-1990s, efforts were directed toward finding or developing a digital rain gauge and telemetry system to replace the analog network. Weighing, optical, tipping bucket, and drop counting gauges were evaluated side by side in both the laboratory and the field. Weighing gauge technology was the only type of these gauges that could accurately measure the large range of intensities observed from winter frontal rainfall and summer thunderstorm rainfall, and the associated diverse drop size distributions. The instrumentation, developed in house, and conceptually

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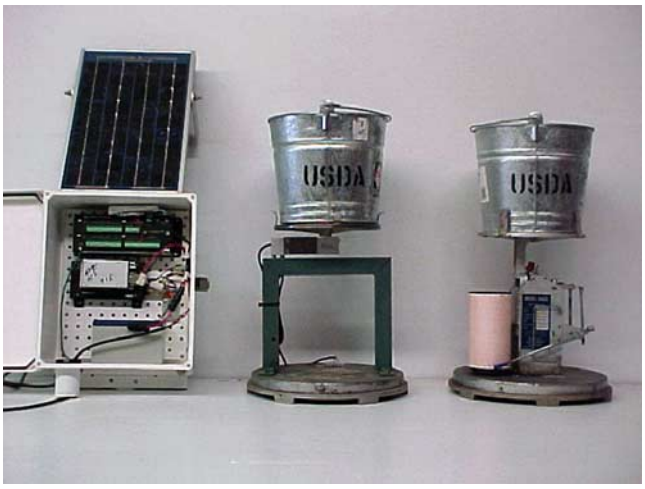

Figure 1. (left) WGEW digital rain gauge battery, telemetry, data logger, and solar panel. (middle) Digital weighing rain gauge, base and frame, strain gauge, and collection bucket. (right) Belfort analog weighing rain gauge, base and frame, mechanical linkage to pen arm and rotating recording drum, and collection bucket.

similar to the design described by *Hanson et al.* [2001], was placed in the same gauge housing as the analog system to minimize the differences between analog and digital gauges caused by wind effects due to the gauge profile. The digital gauges employ an electronic strain gauge in which the weight of precipitation in a collection bucket is converted into a voltage. A linear relationship between voltage and observed precipitation depth was defined for each gauge using a set of calibration weights in the laboratory when the gauge was fabricated. In addition to the basic measurement device, considerable effort was directed to integrating data logging and telemetry electronics, in an attempt to maximize operational reliability and enhance protection from the environment and vandalism. The new digital rain gauge and its associated electronics are pictured next to an analog gauge in Figure 1. Through 1999, the network consisted of analog recording weighing rain gauges. In 2000, the digital gauges were placed adjacent (~1 m separation distance) to the analog gauges. Both the analog and digital network of gauges were in operation from 2000 to 2004 to enable a comparative analysis of the two systems [*Keefer et al.*, 2008]. In regards to precipitation observations they concluded that "1) individual digital rain gauges recorded precipitation equivalently; 2) high errors in event intensities may be produced when analog charts are digitized at short time intervals; 3) for several different measures of precipitation, the analog and digital data were equivalent."

[5] The greatest number of rain gauges in simultaneous operation on the WGEW was 95. Currently 88 gauges are in operation in and adjacent to the WGEW and another 24 are deployed over the larger San Pedro watershed and the Santa Rita Experimental Range. Rain gauge locations in and near the WGEW are illustrated in Figure 2. The web site contains a table with rain gauge coordinates and gauge installation dates.

2.1. Precipitation Record

[6] As noted above the precipitation record is derived from an analog weighing-recording rain gauge network from the inception of the WGEW through 1999. From 1 January 2000 forward, the record is derived from a digital weighing-recording network of rain gauges. The analog data were digitized from paper charts and is stored in breakpoint format (time and accumulated rain depth pairs digitized at breaks in slope of the pen trace on the chart). For the analog network record, different numbers of rain gauges were in operation during different periods of time. The most notable cases were from January 1980 to June 1991 and from October 1998 to October 2004 when the analog operational network was scaled back to nine gauges during the nonmonsoon months because of financial considerations. Analysis by *Osborn et al.* [1979b] indicated that this number of gauges was more than adequate to characterize the variability of the winter frontal rainfall. The exact turn-on and turn-off dates for each of the gauges is part of the database and they are returned with any data query via the web database interface. The precipitation record observed via the digital gauges consists of rainfall depths at 1-min intervals during periods of rainfall.

2.2. Rain Gauge Calibration, Data Processing, and QA/QC

[7] Prior to 1968 there was not a regular schedule of in-field rain gauge calibration. Occasional field checks were made by measuring the amount of rainfall accumulated in the collection bucket with a standard volumetric tube measurement. If differences existed between the measurements, a correction factor was developed from the tube measurement and applied. As of 1968, each gauge was checked and adjusted annually, usually prior to the summer monsoon, with a set of standard weights through the full range of a pen sweep on the analog gauges "with the following sequence of calibrated weights—0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.75, 1.00, 1.25, 1.50, 2.00, 2.5, 3.00, 3.50, etc., to the maximum" [*Chery and Osborn*, 1971, p. 5]. Chart on and off times were set and compared respectively, to the wristwatches of field technicians whose watches were set to a broadcast standard time. If clocks stopped or gained/lost more than 15 min over the course of a 7-d period (weekly gauge visits), the clocks were replaced with spares and the malfunctioning clocks were serviced in Tombstone. In these cases the event start times would be adjusted to account for the fast/slow clock using a linear correction. In the case where a clock stopped, start times from the nearest operating gauge were used. However, because of the daily time resolution of the analog charts and the use of a wrist watch, "time at one gauge at any instance will be, at best, within ±5 minutes with any other gauge in the network" [*Chery and Kagan*, 1975, p. 49]. The voltage to depth relationship of each digital gauge is also verified annually using the calibration weights in the field. Each data logger clock time is checked daily via telemetry and periodically reset to National Institute of Standards and Technology (NIST) standard time. The time kept by the base station computer is manually set to NIST standard time once per month and then all data logger clocks are updated via telemetry to match the base. Though the base station computer may deviate from NIST time by about ±2 min per month, the network of 88 data logger clocks stay within less than one minute of each other and standard time [*Keefer et al.*, 2008].

[8] Data processing and QA/QC of the analog charts has generally been done in four steps [*Chery and Kagan*, 1975]:

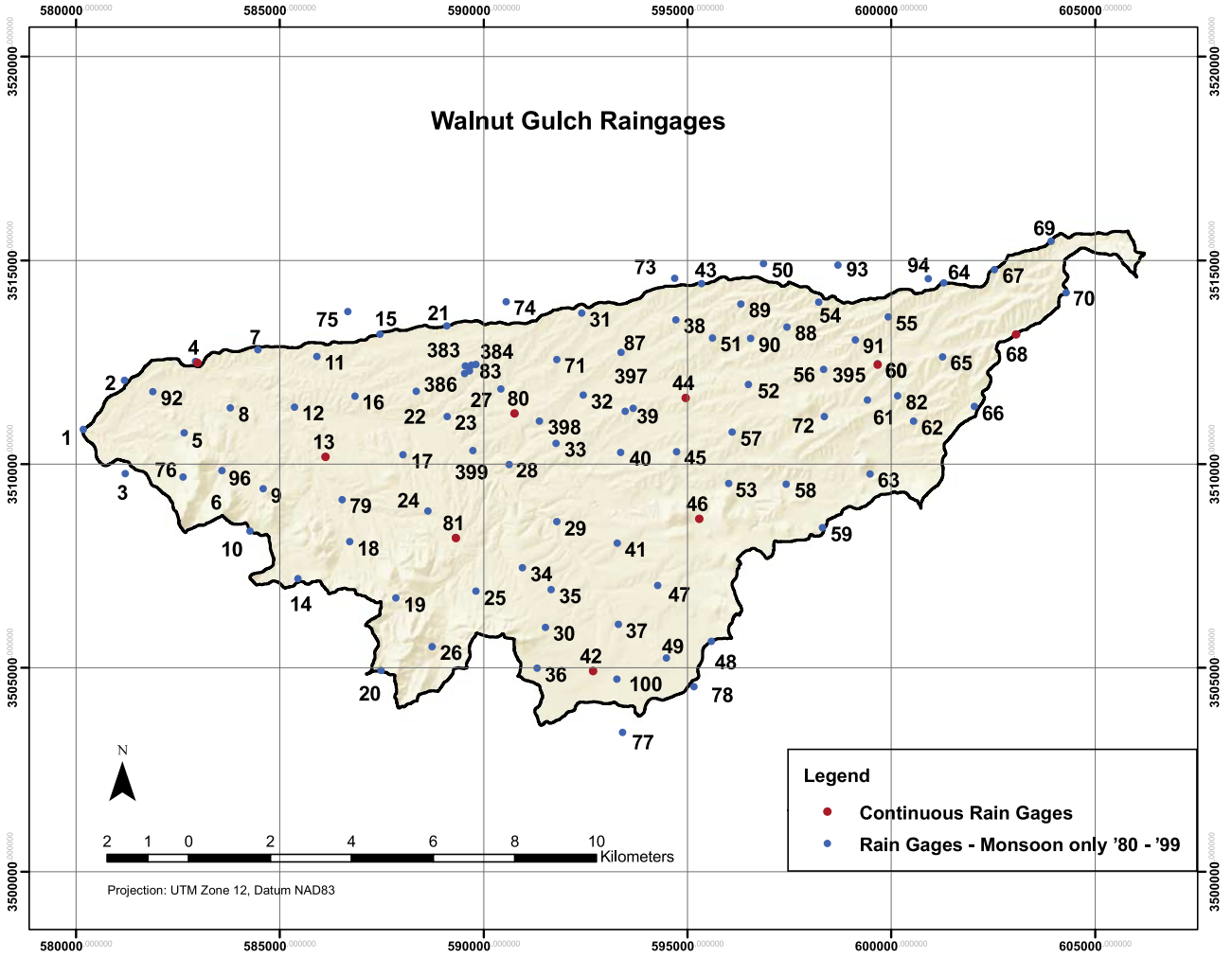

Figure 2. USDA-ARS Walnut Gulch Experimental Watershed rain gauge locations.

(1) chart logging, (2) coding, (3) digitizing, and (4) visual inspection of digitized storm event totals for spatial coherence and to estimate event start and stop times if a gauge clock stopped or storm event totals if a gauge malfunctioned.

[9] Charts are logged in Tombstone shortly after they are retrieved from the gauges and notes are compiled from the charts to aid in data processing. The charts are then sent to the SWRC in Tucson for coding. In this step, the daily and weekly charts are examined side by side to identify events and assign event numbers. For data reduction and QA/QC procedures the following definition of an event was adopted for the network of gauges. An event begins when any one of the gauges in the network detects measurable rainfall. As long as there is not a hiatus of more then 60 min between breakpoints on any of the gauges in the network the event continues until the last breakpoint on any gauge prior to a 60 min hiatus of no measurable rainfall. If rainfall is measured in any of the gauges after a 60 min hiatus over the entire network, it is considered the start of a new event. A technician then digitizes the charts where measurable rainfall is grouped into events. Estimation of the digitization error can be found in work by *Chery and Beaver* [1976], *Freimund* [1992], and *Keefer et al.* [2008]. It should be noted that analog to digital conversion has evolved as technology has advanced (from manual reading, done prior to 1960, to an electromechanical analog to digital converter coupled with a card punch until the mid-1980s, through several solid state electronic digitizing tablets [*Osborn*, 1963; *Chery and Kagan*, 1975; *Keefer et al.*, 2008]).

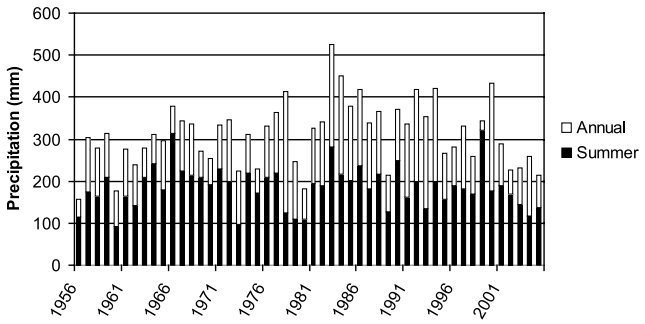

Figure 3. Walnut Gulch Experimental Watershed annual and summer precipitation 1956–2005. Total annual precipitation is the average annual total of six rain gauges (4, 13, 42, 44, 60, and 68). Summer precipitation is the average July, August, and September total of the six rain gauges. The 50-year average annual precipitation is approximately 312 mm, and the 50-year average summer precipitation is roughly 185 mm.

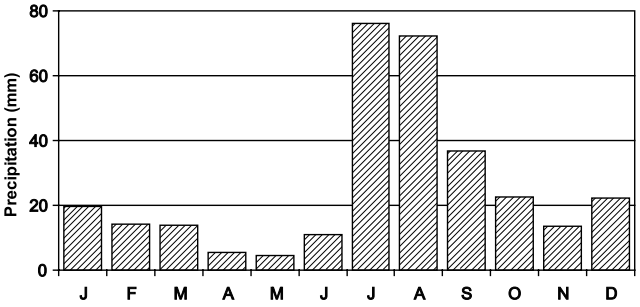

Figure 4. Walnut Gulch Experimental Watershed monthly precipitation 1956–2005. Monthly precipitation is the 50-year average of the average monthly total of six rain gauges (4, 13, 42, 44, 60, and 68).

Digitizing resolution has always been 0.01″ for depth and whole minutes for time, with break points identified by visual inspection. Thus breakpoints consist of time, accumulated rain depth pairs, with nonuniform time intervals and depths that are multiples of 0.01″. Wind corrections were not applied to the data as wind speed and direction are only measured at three locations in the WGEW and not adjacent to each rain gauge. After digitizing is completed, event rainfall totals are plotted by gauge location and isohyetal maps are visually examined for missing data or spurious totals. On the basis of this examination, charts may be reexamined, recoded, and/or redigitized. For spurious or missing data, nearby gauges may be used to provide estimates, which are tagged as such in the database.

[10] *Chery and Kagan* [1975] reported on the amount of estimated analog data for the 6-year period from 1967 to 1972. On an annual basis, the percentage of rainfall duration that was estimated ranged from 3.4 to 12.6 percent. For the same period, the percentage of total rainfall event depth that was estimated ranged from 3.1 to 5.6 percent. It was also found that because of rain gauge accuracy and the processing resolution of the analog gauges, many small events (typically less than 1.27 mm or 0.05 inches) are not measured. The digital rain gauges have substantially decreased the amount of estimated data and timing errors associated with rainfall observations. This, and the implications of the changeover from the analog to digital gauges for a number of hydrologic and meteorological applications are discussed in more detail by *Keefer et al.* [2008].

2.3. General Precipitation Characteristics

[11] The average annual precipitation for the 50-year period from 1956 to 2005, as derived from six, continuous, well distributed WGEW rain gauges, is approximately 312 mm. Interannual variability of both annual and summer rainfall totals (Figure 3) is large. In the case of annual totals, the lowest was recorded in 1956 (~165 mm) and the highest in 1983 (~525 mm). The average monthly rainfall totals are illustrated in Figure 4. Approximately 60% of the total annual rainfall occurs during the summer monsoon (July, August, and September). During the monsoon, precipitation typically results from high-intensity air mass thunderstorms of limited spatial extent. Approximately 35% falls during the winter months from large-area, lower-intensity frontal systems. The reminder typically results from tropical depressions originating in the Gulf of Mexico in July to September or the Gulf of California in late September and October [*Gochis et al.*, 2006].

2.4. Data Availability

[12] All these data can be obtained in a variety of formats and accumulated over various time intervals (daily, monthly and annual) via a web interface at http://www.tucson.ars.ag.gov/dap/.

2.5. Examples of Data Use

[13] The WGEW rainfall network database has been used extensively for a great number of different analyses as well as validation of methods and models. Only several selected examples are described below. For a wider sampling, the reader is referred to the SWRC bibliography at http://www.tucson.ars.ag.gov/unit/Publications/Search.html.

[14] Frequency analyses of point rainfall intensities were recently updated by *Mendez et al.* [2003]. They estimated that 5-min 2-year and 10-year point intensities were 93.7 and 147.1 mm/h, respectively. The 60-min point intensities for the same return periods were 24.1 and 38.3 mm/h. Temporal trends of precipitation from 1956 to 1996 were investigated by *Nichols et al.* [2002] who found an increasing trend in total annual precipitation over this time that was due almost entirely to increases in nonsummer precipitation as a result of a greater number of rainfall events in these seasons. A number of the significant temporal trends found by *Nichols et al.* [2002] were no longer significant when analyzed over the 1956 to 2007 time period [*Goodrich et al.*, 2008].

[15] The high-intensity, summer air mass thunderstorms also produce rainfall totals that vary significantly over short distances. *Osborn et al.* [1979b] found that individual storm rainfall total correlations were not significant beyond a distance of approximately 5 km. *Nichols et al.* [1993] extended this analysis and found increasing correlation lengths as timescales move from daily, to seasonal to annual precipitation totals with winter frontal rainfall being much more spatially uniform than summer precipitation. *Syed et al.* [2003] computed the spatial coverage of over 300 individual rainfall events, as well as the coverage of the storm core (defined as the area experiencing rainfall intensities greater than 25 mm/h and likely to produce runoff) over a range of watershed scales within the WGEW. They found that on average the ratio of the overall storm area to catchment area was approximately 0.4 at the overall WGEW scale but the ratio of the area of the event storm core to catchment area at the same scale was 0.05. They further found that the volume of the storm core was more highly correlated with runoff volume and event peaks (R^2 = 0.71 and 0.76, respectively) than that of total storm volume (R^2 = 0.59 and 0.53, respectively). These and other studies emphasize the importance of obtaining accurate observations of precipitation in time and space, especially in arid and semiarid regions.

[16] **Acknowledgments.** The WGEW precipitation network and its associated 50+ years of high-quality records would not have been possible without the many dedicated USDA-ARS Southwest Watershed Research Center staff in both Tombstone and Tucson, Arizona. The vision and commitment of early ARS and Soil Conservation Service scientists and administrators to construct and operate these and the entire ARS National Experimental Watershed Network for the long term are to be commended.

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