WATER RESOURCES RESEARCH, VOL. 44, W05S05, doi:10.1029/2006WR005733, 2008

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

Jeffry J. Stone,[1] Mary H. Nichols,[1] David C. Goodrich,[1] and Jared Buono[1]

Received 14 November 2006; revised 28 August 2007; accepted 20 December 2007; published 4 April 2008.

[1] Runoff measurement at the semiarid Walnut Gulch Experimental Watershed began in the middle 1950s with five critical depth flumes. Since that time, the measurement network has evolved to include measurement structures on 11 large watersheds (2.27–149 km^2), 8 medium watersheds (0.35–1.60 km^2), and 11 small watersheds (0.0018–0.59 km^2). The ephemeral nature of runoff, high-flow velocities, and high-sediment concentrations in the flow led to the development of the Walnut Gulch supercritical flume used on the large watersheds and the Smith supercritical flume used on the small watersheds. The period of record considered good to excellent ranges from 26 to 47 years. In 1999, the original analog recording systems were augmented with digital recorders. Runoff occurs at Walnut Gulch primarily as a result of convective thunderstorms during the months of July through September. Runoff volume and flow duration are correlated with drainage area as a result of the limited areal extent of runoff producing rainfall and transmission losses or infiltration of the flood wave into the channel alluvium. Runoff records including hydrographs and summary data are available in several formats via a Web interface at http://www.tucson.ars.ag.gov/dap/.

Citation: Stone, J. J., M. H. Nichols, D. C. Goodrich, and J. Buono (2008), Long-term runoff database, Walnut Gulch Experimental Watershed, Arizona, United States, *Water Resour. Res.*, *44*, W05S05, doi:10.1029/2006WR005733.

1. Introduction

[2] The Walnut Gulch Experimental Watershed (WGEW) runoff database has the longest period of record of runoff in the world for a semiarid location. The runoff data have been the basis for semiarid region flood frequency analysis and, in conjunction with rainfall data from the intensive recording rain gauge network, are the basis for understanding rainfall-runoff processes at a range of scales and watershed-scale model development, testing, and validation. Runoff is measured at three ranges of watershed size: small, 0.0018–0.059 km^2; medium, 0.35–1.60 km^2; and large, 2.27–149 km^2. The small watersheds are termed “unit source area watersheds” and were established to quantify the interaction of rainfall intensity patterns, soils, vegetation, and management on the rates and amounts runoff and sediment production. The medium watersheds were established at preexisting small earthen dams or stock tanks to obtain inexpensive measurements of storm runoff volume and annual sediment yield. The large watersheds were established to quantify the effects of the spatial and temporal variability of thunderstorm rainfall and channel characteristics on water yield, peak discharge, and sediment yield. The physical characteristics of the watersheds are detailed by *Skirvin et al.* [2008] (vegetation) and *Heilman et al.* [2008] (land use and location) in this issue.

2. Data Collection

[3] The measurement of runoff at Walnut Gulch is affected by the ephemeral nature of the runoff, high flow velocities, high sediment concentrations in the flow, and the initial upstream channel geometry created by the previous flow(s) sediment transport/deposition. The high sediment loads present a problem for structures that measure runoff stage at critical depth. Structures such as weirs and zero slope flumes retard the flow velocity to tranquil or subcritical conditions that, for sediment-laden flows, cause sediment deposition in the pond above or within the measurement section and invalidate the stage-discharge relationship of the measurement structure. Because of this, runoff measurement at Walnut Gulch has relied on supercritical flumes that channel the flow through the structure at a velocity high enough to minimize sediment deposition within the measurement section. A full discussion of the hydraulic factors involved and the evolution of flume design at Walnut Gulch is given by *Smith et al.* [1982].

[4] Runoff was originally measured using a stilling well, float, and analog stage recorders (Stevens A-35, Friez FD-4, Friez FW-1) [see *Brakensiek et al.*, 1979] with mechanical clocks to record the timing of the event (Note: use of trade names in this report is for information purposes only and does not constitute an endorsement by the USDA-ARS). In 1999, digital recorders consisting of potentiometers attached to the stilling well gear mechanism and a Campbell Scientific CR-10 data logger were added to all of the runoff measurement stations. At present, both the analog and digital data are being collected and are archived.

[5] The history and development of the existing runoff measuring structures, the Walnut Gulch supercritical flume (WGSF), on the large watersheds is discussed by *Renard et*

---

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

Table 1. Large Watershed Period of Discharge Record, Type of Measurement Structure, Watershed Area, Mean Annual Runoff Volume, and the 2 and 100 Year Peak Discharge

Watershed ID	Period of Record	Runoff Measurement Structure[a]	Area, km^2	Area Above Stock Ponds,[b] %	Average Annual Runoff Volume,[c] m^3
63.001	1954–1963, 1964 to present, 1972	OSF, WGSF, PD	149	10	374790
63.002	1953–1958, 1959 to present, 1974	OSF, WGSF, PD	114	14	406143
63.003	1954–1958, 1958 to present, 1973	OSF, WGSF, PD	8.98	44	31818
63.004	1954–1968, 1969 to present, 1979	OSF, WGSF, PD	2.27	0	14167
63.006	1962 to present, 1979	WGSF, PD	95	12	418584
63.007	1966 to present, 1973	WGSF, PD	14	0	32191
63.008	1963–1990, 1972	WGSF, PD	16	9	68419
63.009	1967 to present, 1972	WGSF, PD	24	5	163276
63.010	1967 to present, 1972	WGSF, PD	17	10	54927
63.011	1963 to present, 1971	WGSF, PD	8.24	18	73068
63.015	1965 to present	WGSF	24	29	99919

[a] OSF, original supercritical flume; WGSF, Walnut Gulch supercritical flume; and PD, porous dike installed.
[b] Area above stock ponds is percent of total subwatershed area upstream from stock ponds.
[c] For the period of record after the installation of the WGSF.

al. [2008]. After the WGSFs were constructed, it was observed that flow, particularly the smaller flows, was frequently asymmetrical through the measurement section of the WGSF. The asymmetry was due to the short-approach section of the flume and the variable channel geometry of the alluvial channel directly upstream. On the basis of measurements of flow velocity and design testing using scale models, porous dikes were installed upstream from all of the large flumes with the exception of 63.015 to guide the flow along the centerline of the flume.

[6] Runoff measurements on the medium watersheds began in 1960. Unlike the large and small watersheds, which are instrumented to measure runoff depth via a flume or weir, the medium size watersheds are instrumented to measure changes in water level impounded behind small earthen dams or stock ponds. The changes in water level are converted to runoff volume using a stage-volume relationship derived from pond topographic surveys. Overflow from the ponds is computed on the basis of recorded overflow through either earthen or sharp crested spillways. There are a total of 20 stock ponds on the WGEW of which 8 are instrumented to measure runoff. Details of the stock pond data reduction and records are given by *Nichols* [2006].

[7] Runoff measurements on the small watersheds began in 1962 with the installation of broad crested V notch weirs at 63.101, a shrub dominated site (Lucky Hills) and 63.112, a grass dominated site (Kendall). At Lucky Hills, four additional weirs and an H flume were installed during the period 1963–1965. Four weirs were installed near the city of Tombstone beginning in 1972. However, the weirs on watersheds with well-defined channels had measurement problems associated with the sediment load in that sediment would deposit in the ponds behind the weirs invalidating the weir rating curve. On the basis of the scale model testing of the large flumes, *Smith et al.* [1982] designed a metal supercritical flume (Smith flume or Santa Rita flume) to be used on small watersheds. Currently, runoff at all of the small watersheds with the exception of 63.105, 63.106, and 63.112 is measured with Smith flumes.

[8] The period of record associated with each measurement structures, and the watershed area, and average annual runoff volume for each watershed are listed in Tables 1, 2, and 3. The average annual runoff volume was computed using the analog data for the period of record when the WGSF was operational for each of the large watersheds, for the entire period of record for the stock ponds, and for the entire period of record or when the Smith flumes were installed for the small watersheds. The current subwatershed boundaries are given by *Heilman et al.* [2008, Figure 1]. Annotated images of the current runoff measurement structures are provided at http://www.tucson.ars.ag.gov/dap/.

3. Data Quality

[9] The quality of the runoff records of WGEW has been primarily impacted by the type of measuring structure, the sediment characteristics affecting the alluvial channels upstream from the measuring structures, the sediment load in the flow, and the mechanism used for recording the event. A qualitative assessment of the runoff records based on the first criteria above was done by the unit scientists in 1989 for the large flumes. The quality of the runoff data collected before the installation of the WGSF were considered poor because of the inadequacy of the original structures, data collected after the installation but before the porous dikes were installed were considered fair to good because of the need to compensate for asymmetrical flows, and data collected after the dikes were installed were considered good to excellent. During the period before the dikes were installed, asymmetrical flow was adjusted using field observations of the high-water marks on the far and nearside of the flume [*Smith et al.*, 1982]. The high sediment loads also cause sediment deposition in the intakes of the stilling wells during the recession of the hydrograph, which effectively slows the rate of water exiting the stilling well. The result is a recession curve that slowly approaches zero. Because of this, most of the recessions on the large watersheds have been estimated manually on the basis of observation of flow recession rates during runoff events. For the small watersheds, the period of record before the installation of the

Table 2. Medium Watershed Period of Discharge Record, Type of Measurement Structure, Watershed Area, and Mean Annual Runoff Volume

Watershed ID	Period of Record	Runoff Measurement Structure	Area, km^2	Within Watershed	Average Annual Volume, m^3
63.201	1966 to present	stock tank	0.44	63.001	4853
63.207	1962 to present	stock tank	1.11	63.015	8481
63.208	1973 to present	stock tank	0.92	63.003	12356
63.213	1969 to present	stock tank	1.60	63.015	15216
63.214	1960 to present	stock tank	1.51	63.003	25368
63.215	1966 to present	stock tank	0.35	63.010	8694
63.216	1966 to present	stock tank	0.84	63.011	10047
63.223	1960–1977	stock tank	0.84	63.002	6789
	1985 to present	stock tank	0.84	63.002	6789

Smith flume is considered poor because of invalid rating tables due to sedimentation while the period after is considered good to excellent. For the small watersheds that do not have Smith flumes, the sediment load does not affect the runoff measurement and entire period of record is considered good to excellent.

[10] The analog stage recording system consisted of a mechanical clock, which rotated a drum chart via a gear and a pen activated by changes in water level in the stilling well via a float, gear, and cam mechanism. In the early records, the pens could run out of ink, thus missing the event. The pens were eventually replaced with felt tip pens in the 1980s, which minimized that problem. Problems with the mechanical clocks included failure to rewind the clock, mechanical failure, and inconsistent clock speed. In addition, there was no central synchronization of time throughout the flume and rain gauge network. For the digital data, the recording times for the rain gages and runoff measurement stations are synchronized on a daily basis.

4. General Runoff Characteristics

[11] Runoff at the WGEW is typical of many semiarid regions in that the channels are dry for most of the year. Typically, runoff occurs as the result of thunderstorm rainfall, the flood peak arrives very quickly after the start of runoff, and the duration of runoff is of short [*Keppel and Renard*, 1962]. Two exceptions to the short duration of runoff are watersheds, 63.002 and 63.007, which have had intermittent base flow from the beginning of the respective station record through 1977. Almost all of the annual runoff and all of the largest events occur between July and September as a result of high-intensity, short-duration, and limited areal extent thunderstorms [*Goodrich et al.*, 2008]. On average, there are approximately nine runoff events per year independent of drainage area. Runoff occurs infrequently in the early fall as a result of tropical cyclones and in the winter as a result of slow moving frontal systems both of which cover large areas and have rainfall of low intensities and long durations. Although these fall and winter rainfall events generate little runoff at the WGEW, this is not the case for the San Pedro River just downstream from where Walnut Gulch enters the river. For the same period of record (1963–1996), the top six annual maximum peak flow events at the outlet of the WGEW occurred in the summer months, while for the San Pedro, two of the top six occurred in the fall and two occurred in the winter.

[12] The impacts of infiltration of the flood wave into the dry channel bed (transmission losses) and the location of the

Table 3. Small Watershed Period of Discharge Record, Type of Measurement Structure, Watershed Area, Mean Annual Runoff Volume, and the 2 and 100 Year Peak Discharge

Watershed ID	Period of Record	Runoff Measurement Structure[a]	Area, km^2	Average Annual Runoff Volume,[b] m^3
63.101	1962–1986	VNW	0.013	282
63.102	1963–1972, 1973–1975, 1976–1997, 1998 to present	VNW, SCF, SEF, SRF	0.015	324
63.103	1963–1976, 1977 to present	VNW, SRF	0.037	677
63.104	1963–1977, 1978 to present	VNW, SRF	0.045	598
63.105	1965–1986, 1992 to present	HF	0.0018	49
63.106	1965–1986, 1992 to present	HF	0.0034	75
63.112	1962–1986, 1990 to present	VNW	0.019	328
63.121	1972–1976, 1977 to present	VF, SRF	0.054	839
63.122	1974–1976, 1977–1988	2 ft HF, SRF	0.0097	90
63.124	1974–1976, 1977–1998	RF, SRF	0.022	276
63.125	1980 to present	SRF	0.059	454

[a] VNW, V notch weir; SCF, Smith concrete flume; SEF, Smith extension flume; SRF, Santa Rita or Smith flume; HF, H flume; RF, Replogle flume; and VF, Venturi flume.

[b] For the entire period of record for 63.101, 63.105, 63.106, and 63.112. The period of record for the remainder of the watersheds is after the installation of the SRF or in the case of 63.102, after the installation of the SCF.

rainfall producing runoff on runoff peak and volume are discussed by *Renard et al.* [2008]. These two factors are the basis of strong relationships between drainage area and runoff characteristics typical of semiarid regions with alluvial channels. In contrast with humid regions, the average annual runoff per unit area decreases with watershed area (Figure 1). The long-term average event duration ranges from 40 min for the smaller watersheds to over 300 min for the large watersheds (Figure 2). The outliers in Figure 2, 63.002 and 63.007, are the average event durations when both of these watersheds sustained base flow.

5. Data Availability

[13] The analog and digital runoff data can be obtained from the Southwest Watershed Research Center Web site at http://www.tucson.ars.ag.gov/dap/. Watersheds can be selected by watershed identification number or graphically through a map of the watersheds. Basic queries of the database can be done including event, daily, monthly, and annual summaries, averages, and complete hydrographs and can be output as a Web page, text, or MS Excel file.

6. Examples of Data Use

[14] The wide range of scales of instrumented watersheds and the intensive rain gage network at the WGEW has facilitated research in rainfall-runoff relationships, channel processes, and model development, testing, and validation. Early research focused on describing hydrograph characteristics and the relationship between rainfall and runoff at a range of scales. For the small watersheds, *Kincaid et al.* [1966] found that the decrease in runoff per unit area was valid from the plot to small watershed scale and that runoff was more dependent on rainfall characteristics than grass or shrub cover. *Osborn and Lane* [1969] quantified relationships between rainfall and runoff characteristics, finding that runoff rates and amounts were correlated with rainfall intensity and depth but that the amount of antecedent rainfall accounted for only 8% of the variation in observed runoff. At the larger watershed scale, the decrease of runoff shown in Figures 1 and 2 has been shown to be a result of transmission losses [*Keppel and Renard*, 1962] and the limited areal extent of thunderstorm runoff [*Osborn and Renard*, 1969]. The area of a thunderstorm above a threshold intensity and depth (storm core) has also been correlated with runoff rate and volume respectively [*Osborn and Laursen*, 1973; *Syed et al.*, 2002] and, as with the small watersheds, soil moisture has a secondary importance to the rates and amounts of runoff [*Syed et al.*, 2002]. The availability of runoff data at stations distributed along the main channel reach and tributaries of Walnut Gulch led to the development of an empirical transmission loss equation [*Lane*, 1982, 1983a] and the basin-scale version of the Simulation of Productivity and Utilization of Rangelands model [*Lane*, 1983b]. The effects of the level of spatial discretization of overland flow and channel elements has been studied at the small (4 ha) scale [*Lopes and Canfield*, 2004; *Canfield and Goodrich*, 2006] and large (630 ha) scales [*Goodrich*, 1990]. Relationships have been quantified between drainage area and average annual runoff amount and return period discharge [*Goodrich et al.*, 1997] and the Natural Resource Conservation Service runoff Curve Number [*Simanton et al.*, 1996].

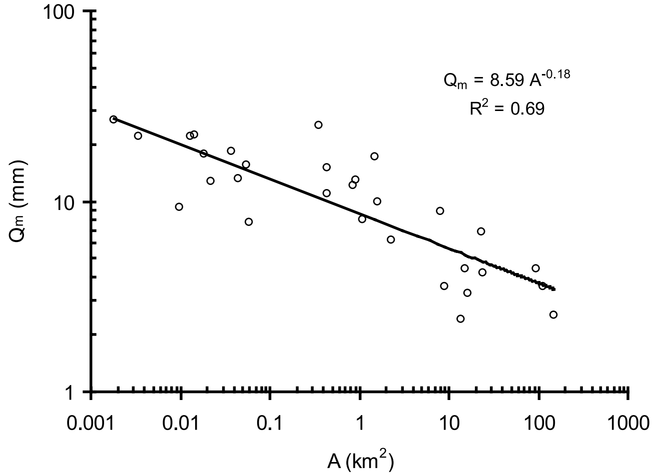

Figure 1. Decrease in average annual runoff volume per unit area, Q_m, with increasing watershed area, A. Period of record used is given in Tables 1–3.

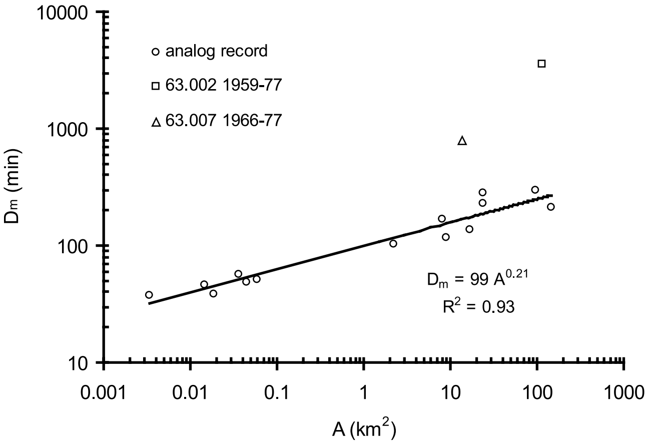

Figure 2. Increase in average runoff event duration, D_m, with increasing watershed area, A.

References

Brakensiek, D. L., H. B. Osborn, and W. J. Rawls (1979), Field manual for research in agricultural hydrology, *USDA Agric. Handb. 224*, 550 pp., U.S. Dep. of Agric., Washington, D. C.

Canfield, H. E., and D. C. Goodrich (2006), Differentiating the impact of parameter lumping from the impact of geometric simplification in modeling runoff and erosion, *Hydrol. Processes*, *20*(1), 17–35.

Goodrich, D. C. (1990), Geometric simplification of a distributed rainfall-runoff model over a range of basin scales, Ph.D. dissertation, Univ. of Ariz., Tucson.

Goodrich, D. C., L. J. Lane, R. M. Shillito, S. N. Miller, K. H. Syed, and D. A. Woolhiser (1997), Linearity of basin response as a function of scale in a semiarid watershed, *Water Resour. Res.*, *33*, 2951–2965.

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

Keppel, R. V., and K. G. Renard (1962), Transmission losses in ephemeral streambeds, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, *88*(3), 59–68.

Kincaid, D. R., H. B. Osborn, and J. L. Gardner (1966), Use of unit-source watersheds for hydrologic investigations in the semiarid Southwest, *Water Resour. Res.*, *2*, 381–392.

Lane, L. J. (1982), A distributed model for small semiarid watersheds, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, *108*(10), 1114–1131.

Lane, L. J. (1983a), Transmission losses, in *SCS National Engineering Handbook Section 4, Hydrology*, chap. 19, pp. 19-1–9-21, Soil Conserv. Serv., U.S. Dep. of Agric., Washington, D. C.

Lane, L. J. (1983b), SPUR hydrology component: Water routing and sedimentation. SPUR—Simulation of Production and Utilization of Rangelands, a rangeland model for management and research, *USDA ARS Misc. Publ. 1431*, pp. 62–67, U.S. Dep. of Agric., Washington, D. C.

Lopes, V. L., and H. E. Canfield (2004), Effects of watershed representation on runoff and sediment-yield modeling, *J. Am. Water Resour. Assoc.*, *40*, 311–319.

Nichols, M. H. (2006), Measured sediment yield rates from semiarid rangeland watersheds, *Rangeland Ecol. Manage.*, *59*, 55–62.

Osborn, H. B., and L. J. Lane (1969), Prediction-runoff relation for very small semiarid rangeland watersheds, *Water Resour. Res.*, *5*, 419–425.

Osborn, H. B., and E. M. Laursen (1973), Thunderstorm runoff in southeastern Arizona, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, *99*(7), 129–1145.

Osborn, H. B., and K. G. Renard (1969), Analysis of two major runoff producing Southwest thunderstorms, *J. Hydrol.*, *8*, 282–302.

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.

Simanton, J. R., R. H. Hawkins, M. Mohseni-Saravi, and K. G. Renard (1996), Runoff curve number variation with drainage area, Walnut Gulch, Arizona, *Trans. ASAE*, *39*, 1391–1394.

Skirvin, S., M. Kidwell, S. Biedenbender, D. King, S. Moran, and C. Holifield Collins (2008), Long-term vegetation transect database, WGEW, Arizona, USA, *Water Resour. Res.*, doi:10.1029/2006WR005724, in press.

Smith, R. E., D. L. Chery, K. G. Renard, and W. R. Gwinn (1982), Supercritical flow flumes for measuring sediment-laden flow, *USDA ARS Tech. Bull. 1655*, 70 pp., U.S. Dep. of Agric., Washington, D. C.

Syed, K., D. C. Goodrich, D. Myers, and S. Sorooshian (2002), Spatial characteristics of thunderstorm rainfall fields and their relation to runoff, *J. Hydrol.*, *271*, 1–21.

J. Buono, D. C. Goodrich, M. H. Nichols, and J. J. Stone, Southwest Watershed Research Center, Agricultural Research Service, United States Department of Agriculture, 2000 E. Allen Road, Tucson, AZ 85719, USA. (jeff.stone@ars.usda.gov)