A brief background on the U.S. Department of Agriculture Agricultural Research Service Walnut Gulch Experimental Watershed

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[1] Watershed research is critical for quantifying the unique characteristics of hydrologic processes worldwide and especially in semiarid regions. In 1953, the United States Department of Agriculture established the Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona, to conduct hydrologic and erosion research. This manuscript (1) provides a historical context summarizing the evolution of the Southwest Watershed Research Center research program, (2) describes significant contributions to instrumentation development and contributions to science, and (3) describes the current WGEW data collection program in the context of contemporary research questions. The development of specialized flumes for streamflow measurement and the establishment of the core monitoring networks are described. WGEW data have been used to quantify semiarid rainfall, runoff, infiltration, and transmission losses; to develop and validate simulation models; and to support broader, regional, basin-scale research. Currently, rainfall, runoff, sediment, meteorology, and flux data collection continue at the WGEW, but the monitoring network has been expanded, and data use has evolved to support several multiple government agencies, universities, and international research programs.

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1. Introduction

[2] Soil and water have long been recognized as fundamental resources sustaining the viability and productivity of society. Increasingly, conservation and efficient use of soil and water resources rely on basic science and resultant technologies. Although watershed research plays an important role in advancing scientific understanding of physical and biological processes therein, as well as in developing solutions to practical problems, watershed-scale research programs have a relatively recent history. The science of hydrology was greatly advanced during the first half of the 20th century through research on infiltration [*Green and Ampt*, 1911] and overland flow [*Horton*, 1933]. Research in the related fields of hydraulics and sediment transport [*Rouse*, 1961; *Chow*, 1964; *Einstein*, 1950], evaporation and transpiration [*Penman*, 1948; *Thornthwaite and Mather*, 1955]; as well as quantitative [*Horton*, 1932, 1945] and fluvial [*Leopold et al.*, 1964] geomorphology further advanced the science of hydrology. Watershed research programs became important for integrating these scientific disciplines and continuing the advance of a broad range of watershed process research. Within the USDA, specific concerns for soil and water conservation led to the expansion of a national watershed research program in the 1930s and again in the 1950s that could build upon and integrate prior scientific advances to address national soil and water problems and to understand the effect of conservation practices on their distribution, quality, and yield.

[3] Watershed research programs such as that implemented at the Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona exemplify a USDA research program built on a continuous long-term core data collection network with the flexibility to address contemporary watershed issues through an evolving research program. The focus of this manuscript is on nonforested research watersheds managed by the USDA.

[4] The objectives are (1) to provide a historical context summarizing the evolution of the Southwest Watershed Research Center (SWRC) research program, (2) to describe significant contributions to instrumentation development and contributions to science, and (3) to describe the current WGEW data collection program in the context of contemporary research questions.

2. Early USDA Research in Nonforested Regions

[5] Within the western United States, specific efforts to study the relationship between land use and soil and water resources did not begin until the early 1900s. The range-

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lands of the western USA were settled rapidly during the late 1800s and early 1900s with little thought given to conservation in the face of abundant supplies of grass and timber. Many acres of rangeland were severely overgrazed and left subject to severe erosion during this period. The problems were not wholly unacknowledged, and as early as 1903 research programs were being developed to address some of the biological resource concerns at the Santa Rita Experimental Range near Tucson, Arizona, and 4 years later at the Jornada Experimental Range near Las Cruces, New Mexico. However, the need remained for more and better data describing rainfall, runoff, and sediment loads.

[6] In 1912, two 10-acre plots in the Manti National Park/Forest in central Utah were set up to quantify erosion and runoff within an overgrazed rangeland. This research was one of the first demonstrations of the impacts of overgrazing on reducing the soil's water holding ability [*Sampson and Weyl*, 1918; *Chapline*, 1929; *Stewart and Forsling*, 1931].

[7] During the 1920s the call for a national response to the nation's soil erosion crisis was led by Hugh H. Bennett. His early crusades along with his evangelistic zeal led to congressional action in 1929 that established 10 erosion experiment stations (most located in the Midwest). In addition to measurements on small watersheds, extensive experiments were carried out on small plots with portable rainfall simulators [*Beutner et al.*, 1940]. His concerns were catastrophically dramatized during the 1930s as North America experienced disastrous dust storms that had direct, damaging, and long-lasting impacts on U.S. agriculture. Hugh H. Bennett's continuing efforts undoubtedly had more influence on soil conservation efforts in the United States than any other single person leading to his recognition as the "father of soil conservation."

[8] Prior to the establishment of the Agricultural Research Service (ARS) in 1953 as the primary research arm of the USDA, several agricultural soil and water research programs were established by the Operations and Research Division (ORD) of the USDA Soil Conservation Service (SCS). A series of experimental sites located in Arizona and New Mexico (Table 1) were developed in the 1930s and 40s including instrumented watersheds at the Navajo Experiment Station near Mexican Springs, New Mexico; in Albuquerque and Santa Fe, New Mexico; and near Safford, Arizona. These sites were to provide data in support of natural resource conservation measures specifically involving farmers and ranchers. USDA research at the Navajo Experiment Station [*Lowdermilk*, 1936] began in 1934 to provide information on precipitation and the role of runoff rates and amounts on the design of soil and water conservation structures such as water spreaders. Water spreaders, or berms, constructed perpendicular to flow along the contour in upland areas, were a useful mechanism for diverting water from small ephemeral concentrated flow paths to provide supplemental water for adjacent grasslands. The research site included soil conservation demonstration projects to educate farmers and ranchers on conservation methods and their impacts on soil, water, and vegetation. In addition, a comparatively dense instrumentation network with rainfall and runoff measurements from nested subwatersheds provided baseline data to couple with erosion measurements. These watersheds located on the Navajo Indian Reservation of northwestern New Mexico were the earliest instrumented (approximately 400 ha) rangeland watersheds in the southwestern United States. The watersheds were operated through the late 1940s. The USDA rangeland watersheds near Albuquerque and Santa Fe, New Mexico, and near Safford, Arizona, were instrumented with rainfall, runoff, and sediment measuring infrastructure in the late 1930s. Infrastructure development at these watersheds was aided by Civilian Conservation Corps personnel, but measurement was hampered by the lack of instruments designed for semiarid hydrologic and geomorphic conditions.

[9] Through the first half of the 20th century, most available rainfall, runoff, and sediment measuring equipment was based on designs for use in the more humid eastern United States. For example, standard broad crested V notch weirs [*Holtan et al.*, 1962; *Ruff et al.*, 1977; *Brakensiek et al.*, 1979; *Johnson et al.*, 1982], were installed in ephemeral channels at the Safford watersheds to quantify flow characteristics which was necessary for interpreting measurements of sediment. During this time period, there were very little data to understand the magnitude of flooding and sediment loads in the semiarid southwestern United States. Sediment loads during infrequent flash flows were much greater than those experienced in typical eastern U.S. perennial flows. As a result, sediment accumulations behind the weirs rendered the flow measurements useless and required significant maintenance (Figure 1).

3. Southwest Watershed Studies Group

[10] The need for better equipment, measurement methods, and information from large, complex watersheds led to the formation of the Southwest Watershed Studies Group, which was established in 1951 by the SCS-ORD. This group was charged with identifying and recommending watersheds suitable for long-term hydrologic research on southwestern rangelands. A major research objective for the rangeland watersheds selected for study was to determine if conservation practices would affect water yields, sediment movement and other environmental factors. Among the reasons for these objectives was the concern of water users, such as irrigators, that range conservation programs might deplete the water supplies of downstream users.

[11] The study group consisted of a team of scientists and engineers led by J. Linton Gardner, Joel Fletcher, and Willis Barrett. The group traveled throughout Arizona, New Mexico, and southern Colorado to identify and recommend watersheds suitable for long-term hydrologic research on rangelands. Several criteria were developed for the watershed selection process, primarily focusing on the physical attributes of the watersheds. Specific criteria for watershed selection included size, topography, rainfall amount, and vegetation. The selected watershed should range up to 260 km^2, with coincident subterranean and topographic divides, and secondary tributaries to a main channel that might furnish irrigation water. Watersheds were desired with 250 to 410 mm of annual precipitation. The dominant vegetation desired included range grasses (blue and black grama and their associated species replacing existing shrub/cacti species) with little or no

Table 1. Experimental Watersheds Operated by USDA ARS and Predecessors for Arizona and New Mexico

Location	Altitude, m	Predominant Land Use	Cover	Record Years	Number of Watersheds	Responsible Group
Mexican Springs, 32 km N of Gallup, New Mexico	1525–1830	grazing	Mixed grass-brush	1934–1950	12	Navajo Experiment Station, USDA Plant Industry and Navajo Indian Nation
middle Rio Grande, 64 km NW of Albuquerque	1525	grazing	grassland	1939–1975	3	Albuquerque watersheds, USDA SCS and Laguna Indian Reservation
64 km east of Santa Rosa, New Mexico	1370–1675	grazing	mixed grass-brush	1954–1979	3	Alamogordo Creek, USDA SCS, USDA ARS
27 km SE of Capitan, New Mexico	1830	grazing	mixed grass	1966–1983	3	Fort Stanton Watershed, USDA ARS NMSU
40 km N of Las Cruces, New Mexico	1220–1525	grazing	mixed brush	1906 to present	2	Jornada Experimental Range, USDA ARS
San Carlos Basin, within 64 km from Safford, Arizona	1220–1525	grazing	mixed grass-brush-cacti	1939–1975	4	Safford Experimental Watersheds, USDA SCS, USDA ARS, USDI BLM
Tombstone, Arizona	1280–1525	grazing-urban	mixed brush-grass	1954 to present	>20	Walnut Gulch Experimental Watershed USDA SCS, USDA ARS
48 km E of Green Valley, Arizona	1160–1370	grazing	mixed brush-grass-cacti	1975 to present	8	Santa Rita Experimental Range, USDA ARS, Univ. of Arizona
Upper Rio Grande basin	975–1065	grazing	sparse grass	1940–1947	3	Santa Fe, New Mexico, USDA SCS
Upper San Pedro Basin	1065–2135	grazing-urban mining	mixed brush grass-cacti-forest	1930 to present	>25	Charleston, Arizona, USDA ARS, USDA NRCS, USGS, Univ. of Arizona

cultivated land. It was also desirable that the vegetation be capable of recovering from a deteriorated condition. In addition, the watersheds selected should not have major water losses to deep percolation and should be in a significant sediment producing area. Furthermore, the watersheds should be accessible during stormy periods and contain sufficient channel bedrock upon which to construct gauging stations. Cooperation with ranchers within the area was also an important consideration because access to experimental equipment over private property was necessary. A total of 39 watersheds were considered, and in 1953 two watersheds were selected, Alamogordo Creek in New Mexico, and Walnut Gulch in Arizona.

[12] In 1953, the SCS-ORD was reorganized and both personnel and research programs were transferred to the newly formed USDA Agricultural Research Service (ARS). Work to instrument these two large, heterogeneous watersheds began in 1953–1954 with limited success because of inadequate funding to complete the rain gauge networks and construct adequate runoff measuring stations.

4. Senate Document 59 and Advances in ARS Watershed Research Programs

[13] The continuing need for fundamental data, and pressure on natural resources in the face of increasing agricultural, industrial, and population needs, led to a request of the USDA by the Committee on Appropriations of the U.S. Senate to "make a study of the facility needs for research on soil and water problems" [*U.S. Senate*, 1959, p. VI]. This study was conducted with consideration of variation in physical regions across the US and the urgency of the need for additional research to address problems specific to each region [*U.S. Senate*, 1959]. Senate document 59 outlined a comprehensive plan of national laboratories to address agricultural problems of nationwide interest, including issues related to natural resources and the environment. This document identified water supply for irrigation and "the special problems in watershed hydrology because of local flash floods and intense transport of sediment" [*U.S. Senate*, 1959, p. 63] as primary problems in the southwestern United States. The document recommended that the existing Southwest Watershed Studies Group in Tucson, Arizona, "be provided with the means to become a headquarters for research on the watershed hydrology problems of the Southwest as well as providing for an expansion of range management research" [*U.S. Senate*, 1959, p. 65].

Figure 1. Illustration of the sediment accumulations upstream from a broad crested weir on watershed W-5 at Safford, Arizona. Sediment removal from the pond above the weir is required to maintain hydraulic flow conditions.

[14] The Southwest Watershed Research Center (SWRC) was established in 1961 in Tucson, Arizona [*Renard et al.*, 1993]. Funding provided for the outdoor laboratories at Walnut Gulch near Tombstone, Arizona, and Alamogordo Creek near Santa Rosa, New Mexico, accelerated instrumentation and data collection. The SWRC also assumed responsibility for the continuing data collection at the experimental watersheds near Albuquerque, New Mexico, and Safford, Arizona (Table 1). Data collection at these New Mexico and Safford watersheds was discontinued in 1979 because of budget constraints and problems with maintaining the weirs.

5. Walnut Gulch Experimental Watershed, Tombstone, Arizona

[15] The 149-km^2 (58-mile^2) Walnut Gulch Experimental Watershed (WGEW) is a tributary to the San Pedro River of southeastern Arizona and includes the historic city of Tombstone. The areas near Tombstone had been seriously overgrazed during the late 1800s through the early 1900s and were invaded by desert shrubs which dominate the lower two thirds of the watershed. Desert grasses dominate the upper one third. The watershed is assumed to be representative of the black grama desert shrub vegetation complexes of southeastern Arizona, southwestern New Mexico, northeastern Sonora and parts of northern Chihuahua, Mexico. Initial instrumentation efforts were directed toward collecting precipitation and flood hydrology data.

[16] Flood runoff, water yield and sediment production studies were the primary focus of research at WGEW in 1953. Flood design information characterizing southwestern climate and watershed physical features was urgently needed for designing soil and water conservation and flood prevention structures and practices; however progress first required the development and construction of runoff measuring devices suitable for measurement in flash flow conditions. Runoff measurements would be coupled with rainfall data collected through a network of gauges averaging about one per gauge 1.5 km^2 over the entire 149 km^2 watershed.

6. Contributions to Hydrologic Science From WGEW

[17] Experimental watersheds in Arizona and New Mexico have provided valuable outdoor laboratories for studies of semiarid surface water hydrology for more than 50 years. Early contributions of WGEW research to hydrologic science include (1) improved experimental techniques and equipment, (2) advances in the characterization of rainfall and runoff, and (3) improved analytical methods and hydrologic simulation models.

6.1. Supercritical Depth Flume

[18] The challenges involved in beginning the instrumentation of these watersheds in the mid 1950s were truly daunting. There simply were no reliable data available to choose the design flow rate for runoff measurement structures of the size needed at the WGEW and experience with the V notch weirs suggested that specialized instruments were needed to measure runoff. The need for specialized flumes to measure sediment laden flow was recognized by *Wilm et al.* [1938] and led to the development of the San Dimas Flume. This critical depth flume had a rectangular cross section which was not sensitive to low flow rates and didn't conform well to alluvial channel sections, so was not suited to semiarid watersheds. The lack of a suitable flume design and hydrologic data, as well as funding constraints that resulted in pressures to build too rapidly, had disastrous consequences for the first flumes constructed at Walnut Gulch.

[19] During 1953–1954, five large trapezoidal critical depth runoff measuring flumes were constructed with design capacities ranging from 43 to 225 m^3 s^{-1} (1500 to 8000 ft^3 s^{-1}). A sparse rain gauge network of 30 gauges was established. A sequence of storms began in late July 1954 and continued with generally not more than 24-h interruption until late August. By the end of the season only one of the five flumes remained intact and operational. The structures failed because they were (1) hydrologically undersized, (2) hydraulically inadequate, and (3) structurally incapable to withstand the loads involved. These failures stimulated a joint project with personnel of the ARS Hydraulic Structures Laboratory in Stillwater, OK [*Gwinn*, 1964; *Gwinn*, 1970; *Brakensiek et al.*, 1979; *Smith et al.*, 1982] to develop, test, and calibrate new runoff measuring flumes for high-velocity, sediment laden flow conditions. The resulting Walnut Gulch Supercritical Flow Flume became an accepted standard for basic flow-measuring structures at the ARS semiarid watersheds.

[20] The first flume with the newer design was built on Walnut Gulch in 1957–1958 [*Stone et al.*, 2008]. Additional flumes were built on major watershed tributaries before the hydraulic measuring device was constructed at the outlet of Walnut Gulch in 1964. The outlet measuring structure included an energy dissipater at the end of the flume (Figure 2) because the laboratory model studies of the site completed by *Gwinn* [1964, 1970] predicted a scour hole immediately downstream from the flume that might lead to structural failure. The view of the structure immediately after construction shows details of the energy dissipater. The flume has a capacity of 625 m^3 s^{-1} (22,000 ft^3 s^{-1}). Although no discharge that large has been experienced, an estimated 425 m^3 s^{-1} (15,000 ft^3 s^{-1}) flow in 1957 prior to completion of the current flume was used as a guideline for the needed flow capacity at the watershed outlet. Further improvements have been made in critical depth flumes, including designs for smaller watersheds that can be constructed of steel as well as concrete [*Smith et al.*, 1982]. A more detailed description is provided by *Stone et al.* [2008].

6.2. Characteristics of Thunderstorm Rainfall

[21] In the 1950s, the lack of basic hydrologic data limited not only instrumentation, it severely hampered the ability to predict rainfall and flood magnitudes, with implications for safety as well as engineering designs. The initial rainfall network consisted of approximately 30 recording rain gauges (funds limited the number of gauges in the original efforts). From observations in comparison with recorded rainfall, it quickly became apparent that more gauges would be needed to measure spatially limited

Figure 2. The hydraulic measuring device and energy dissipater at the outlet of Walnut Gulch [*Gwinn*, 1964; *Smith et al.*, 1982]. The photograph was taken prior to any flow through the measuring station.

thunderstorm rainfall. The current network consists of 85 recording precipitation gauges representing an area slightly larger than the surface drainage [*Goodrich et al.*, 2008].

[22] Prior to the establishment of the dense rain gauge networks at Walnut Gulch and Alamogordo Creek, there was only limited data documenting thunderstorm patterns and the relation of rainfall to runoff. When concurrent measurements of rainfall and runoff became available, efforts were made to test state of the art techniques such as the unit hydrograph or the rational method to estimate runoff. It soon became very apparent that these techniques could not be used for watersheds where storm rainfall covered only a portion of the watershed.

[23] Information on the evolution of thunderstorm intensity fields in space and time in the southwestern United States was limited. The mechanics of thunderstorm rainfall had been described in an interagency report entitled "The thunderstorm" [*Weather Bureau*, 1949], but details of measured spatial and temporal patterns didn't emerge until rainfall data from Alamogordo Creek and Walnut Gulch were available. Storms in northeastern New Mexico are generally larger in areal extent [*Osborn*, 1983, Figures 26, 27, 28] than most storms in southeastern Arizona and because they are larger in extent and total depth, they generally result in more runoff at the watershed outlet (longer-duration flow but not necessarily greater peak discharge per unit area) [*Renard et al.*, 1970]. Because of channel differences and storm characteristics, the volume of storm runoff from Walnut Gulch is generally smaller than occurs for storms in eastern New Mexico.

[24] Thunderstorms in Walnut Gulch can be illustrated with isohyetal maps such as those shown in Figure 3. The first portion Figure 3 shows the monthly storm totals for August 1982. The summer and annual totals in Figure 3 illustrate that the high spatial variability occurs with considerable regularity. A 2:1 ratio between monthly maximum and minimum point values in the watershed is commonly observed although the location of the peak amount seems to be quite random in location. The variability illustrates problems with trying to use a central gauge value (e.g., Tombstone, located near the watershed center) to model runoff or for other hydrologic information.

[25] In a series of publications, *Smith and Schreiber* [1973, 1974] and *Smith* [1974] presented a detailed analytical description of thunderstorm characteristics in southeastern Arizona. These publications, plus others listed by *Goodrich et al.* [2008] formed the basis of the *NOAA Atlas 2* for Arizona [*Miller et al.*, 1973a, 1973b]. The NOAA NWS reports are a widely accepted source of climate information throughout the USA. Fundamental characterization of thunderstorm rainfall patterns and mechanics coupled with runoff response was an important contribution of research conducted on the WGEW.

6.3. Transmission Losses and the Water Balance

[26] The important role of infiltration of surface runoff into channel alluvium, or transmission losses, was recognized in the early years of measurements at Walnut Gulch. The term "transmission losses" was borrowed from irrigation usage. For many watersheds in the southwestern United States, the net result of transmission loss is that water yield from basins with extensive alluvial channels are characterized by decreasing surface runoff per unit area with increasing watershed size. An example of runoff from an air mass thunderstorm on the upper reaches of Walnut Gulch and subsequently measured at the three main channel measuring stations, flumes 6, 2, and 1 (Figure 4) illustrate how a storm runoff event is affected by "transmission losses." Of special interest is that the peak discharge and storm volume decrease as the advancing flood wave moves over the normally dry channel. In many storm events, the runoff originating at the upper elevations of the watershed completely infiltrates into the channel alluvium before reaching the watershed outlet.

[27] Transmission losses have been quantified during most summer monsoon storm events on Walnut Gulch. *Lane* [1983] authored a chapter (19) in the SCS National Engineering Handbook which provides estimates of channel infiltration losses in ephemeral stream areas. This publication is widely recognized as a needed design consideration for flood prediction, water supply, and groundwater recharge in ephemeral channels throughout the world. The type of data illustrated in Figure 4 has been very useful in developing models of unsteady channel flow with infiltration.

[28] The water balance of Walnut Gulch (Figure 5) is representative of what happens in ephemeral stream areas where runoff traverses dry alluvial streambeds. The total amount of water varies appreciably from year to year and is a function of drainage area size. Precipitation variability dominates the average conditions given in Figure 5. Using the 350 mm average input precipitation, approximately 327 mm is detained on the surface and infiltrates the land surface. Essentially all of the water infiltrated on hillslopes either evaporates or goes back to the atmosphere by transpiration from the sparse vegetation.

[29] On the basis of data collected from relatively small homogeneous watersheds, approximately 23 mm of the incoming precipitation is in excess of the amount intercepted by vegetation or that infiltrates and is referred to as "onsite runoff." A significant portion of the runoff that moves over the land surface and into dry alluvial channels,

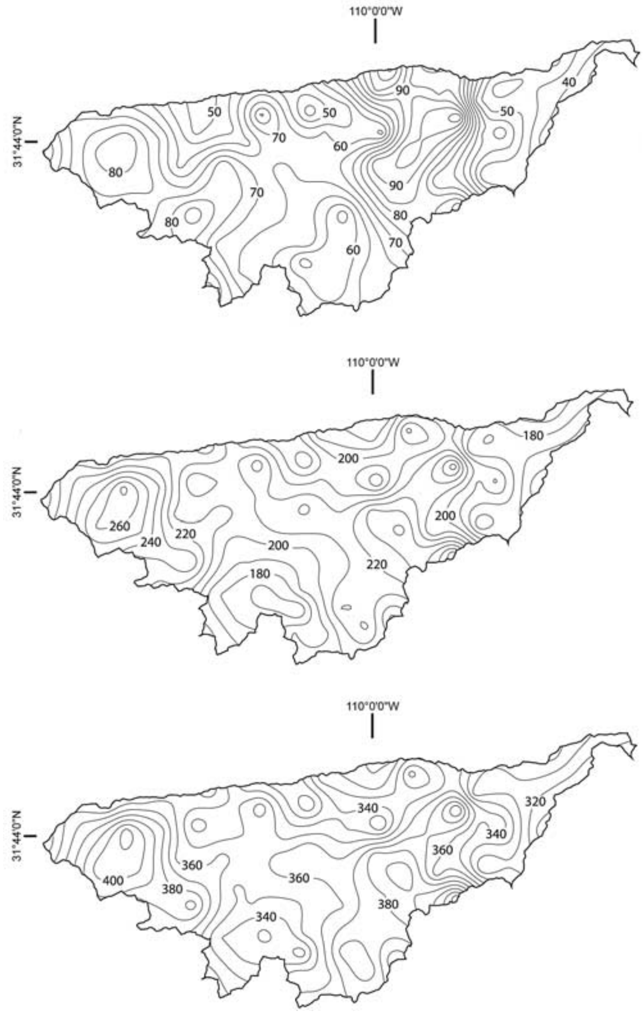

Figure 3. Monthly, seasonal, and annual precipitation variability in 1982 (T. O. Keefer and SWRC staff, Walnut Gulch experimental watershed, mimeographed brochure, 2003, Southwest Watershed Research Center, Tucson, Arizona).

infiltrates into channel alluvium as a transmission loss. Approximately 20 mm a^{-1} of transmission losses occur (varying according to drainage area size) with about 2 mm a^{-1} of surface runoff measured at the watershed outlet (Figure 5) [*Renard*, 1970] (see also T. O. Keefer and SWRC staff, Walnut Gulch experimental watershed, mimeographed brochure, 2003, Southwest Watershed Research Center, Tucson, Arizona). Occasional larger runoff events from infrequent "tropical storms" in September/October originating in Baja California (Mexico) and moving into southwestern U.S. areas may have a larger percentage of runoff than that shown in Figure 5.

[30] The 20 mm a^{-1} of transmission losses (on Walnut Gulch) contributes to groundwater recharge as well as transpiration and evaporation from vegetation along the channel system. Early geophysical studies at WGEW [*Libby et al.*, 1970], groundwater isotope and water level monitoring, repeat microgravity measurements, runoff monitoring and modeling and extrapolation of sap flow monitoring were combined to illustrate that ephemeral channel recharge can be a significant component of overall basin recharge in wet monsoon years [*Goodrich et al.*, 2004]. These results are difficult to extrapolate because of geologic variability along channels. Where channels are well connected to regional aquifer alluvium channel infiltration extending to regional groundwater provides considerable groundwater recharge. In other channel segments, shallow impermeable materials restrict significant deep percolation and result in saturated riparian alluvium following major runoff periods. These perched water tables provide a water source for phreatophytes and seasonal streamside vegetation [*Renard et al.*, 1964]. It is significant to note that potential evaporation as measured with a class A U.S. Weather Bureau pan is about 2600 mm a^{-1} or approximately 7.5 times annual precipitation.

6.4. Expanded Field Research

[31] The watershed research program at the SWRC was expanded in 1975 to include instrumentation of small watersheds on the Santa Rita Experimental Range 30 miles east of Green Valley, Arizona. A hydrologic network was established in cooperation with the U.S. Forest Service. Eight small (less that 5 ha) rangeland watersheds were instrumented with supercritical flow measuring structures [*Smith et al.*, 1982], and precipitation input to the watersheds is measured with 11 recording precipitation gauges. The watersheds are representative of rangelands on alluvial fans at the base of mountain ranges in southeastern Arizona with mixed grass and brush vegetation subjected to various grazing rotations. Hydrologic data collected at the SWRC watersheds compliments biotic and abiotic studies that have been completed during the past 100 years on the SRER [*McClaran et al.*, 2003; *Lane and Kidwell*, 2003].

6.5. Natural Resource Simulation Modeling

[32] The staff of the Southwest Watershed Research Center (SWRC) has been active in multilocation and multidiscipline resource modeling efforts for USDA ARS. These efforts, which began in the late 1970s, involved most of the center staff, either in model conceptualization or in preparation of data with which the models have been calibrated or validated. The Walnut Gulch field data have been an invaluable resource for testing hydrologic models for rangeland conditions including mixed grass-brush environments, where spatially and temporally variable precipitation, and transmission losses dominate the hydrologic cycle. Furthermore, soil erosion by water and transport of the eroded materials through the normally dry streams during the ephemeral storm events is a major environmental concern.

[33] Table 2 enumerates many natural resource models developed by scientists and engineers at SWRC and from similar disciplines at other ARS and academic locations having application in semiarid rangeland areas such as are encountered in Arizona and New Mexico. Table 3 lists some of the technical details of the models listed in Table 2. The models were developed over a period of years by hydrologists, soil scientists, and engineers concerned with natural resources (primarily water, erosion/sedimentation, and chemical transport) at the SWRC, and

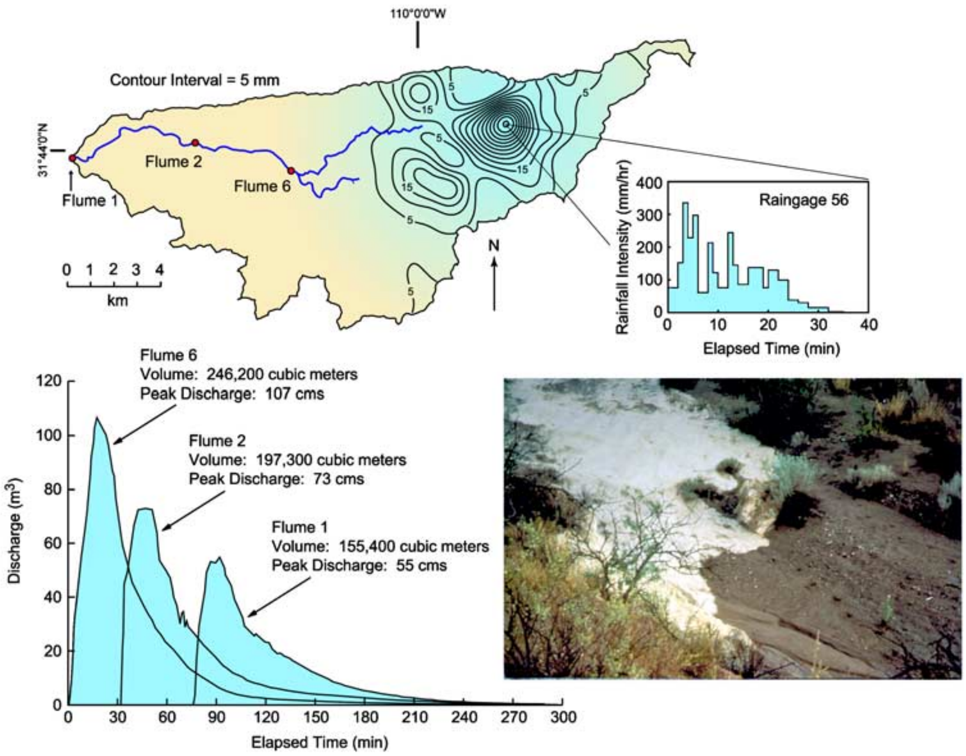

Figure 4. Storm event typical of those occurring on Walnut Gulch as measured downstream and including the watershed outlet [*Goodrich et al.*, 1997].

often in collaboration with cooperators in other government agencies, university students, and faculty.

7. Evolving Research Objectives

[34] Since 1953 the research objectives of the SWRC program have built upon and evolved around the core monitoring network. Research during the decades of the 1950s and 60s was directed toward developing fundamental characterizations of rainfall and runoff and their interactions. In the 1970s water quality concerns became a national priority and significant resources were dedicated to quantify sediment and nutrient loads on the watershed. This research evolved to support simulation modeling through the 1980s and the present.

[35] Natural resources research priorities continually change in response to changing societal concerns and evolving land management priorities. However, water will continue to be a high-priority focus in semiarid regions

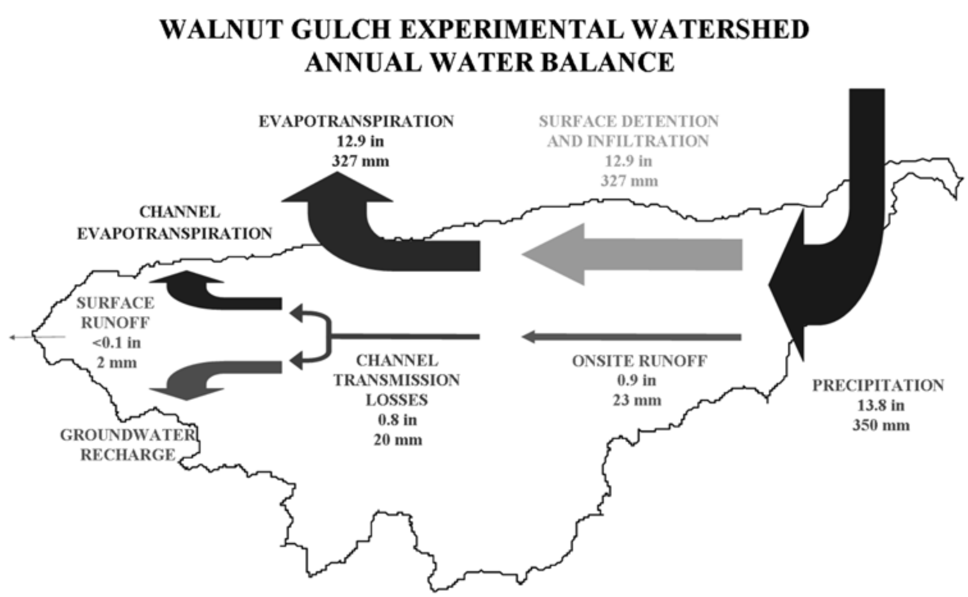

Figure 5. The water balance of the Walnut Gulch Experimental Watershed [*Renard*, 1970; Keefer and SWRC staff, mimeographed brochure, 2003].

Table 2. SWRC Hydrologic Models, National ARS Resource Models, Acronym, Author, and Publication Date

Model Acronym	Title	Source and Publication Date
ACTMO	agricultural chemical transport model	*Frere et al.* [1975]
AGNPS	AnnAGNPS agricultural nonpoint source pollution	*Young et al.* [1987], *Bingner and Theurer* [2001]
CREAMS/GLEAMS	Chemicals, Runoff, Erosion and Agricultural Management Systems/Groundwater Loading Effects of Agricultural Management Systems	*Knisel* [1980], *Leonard et al.* [1987]
EPIC	erosion productivity impact calculator	*Williams et al.* [1983], *Williams and Renard* [1985]
KINEROS	kinematic runoff and erosion model	*Woolhiser et al.* [1990]
KINEROS and AGWA	kinematic runoff with geospatial watershed assessment	*Semmens et al.* [2006]
RUSLE	revised universal soil loss equation	*Renard et al.*, 1997
SPUR	Simulation of Production and Utilization of Rangelands	*Wight and Skiles* [1987]
SWRRB	Simulator for Water Resources in Rural Basins	*Williams and Berndt* [1977], *Williams et al.* [1985]
Stewart Report	water pollution control	*Stewart et al.* [1975]
USDAHL	USDA Hydrology Lab model	*Holtan et al.*, 1975
WEPP	Water Erosion Prediction Project model	*Lane and Nearing* [1989], *Laflen et al.* [1991]

throughout the globe, and deteriorated or fragmented watersheds will adversely affect both water yields and water quality. Continued research into the relation between surface and groundwater will be important to address water supply issues as demands for clean water continue to rise.

[36] The future impact of scientific work at the WGEW depends on the ability of researchers to adapt their research programs, which increasingly requires interdisciplinary approaches, while optimizing the use of the core data collection such that its continued support is justified. Many of the early research objective that required temporally distributed data, such as quantifying thunderstorm characteristics and flood frequencies have been met. However, the value of maintaining these data collection efforts continues to increase especially as longer-term, cyclic climate patterns, such as El Nino and the Pacific Decadal Oscillation, are identified. This flexibility has made, and continues to make long-term data collection at WGEW sustainable, relevant and inherently valuable (M. S. Moran et al., Value

Table 3. Southwest Watershed Research Center and Agricultural Research Service Hydrologic Model Details

Model Acronym	Process Simulated	Simulation Continuous	Simulation Storm	Rainfall Excess Computation	Input Needs	Timescale	Space Scale
ACTMO	watershed hydrology erosion and chemical transport	X	X	Holtan infiltration	watershed data and climate data	hourly	field zones
AGNPS	watershed hydrology nonpoint source pollution		X	SCS curve number	cell and watershed characteristics watershed description and climate data	daily	cell basis for large and small watersheds homogenous fields
CREAMS -GLEAMS	hydrology, erosion, and chemical transport	X	X	modification of SCS curve numbers	watershed description and climate data	daily	homogenous fields
EPIC	hydrology, erosion, and soil productivity	X	X	modified SCS curve numbers	climate and pedon data	daily	homogenous pedons
KINEROS	hydrology and erosion		X	Smith-Parlange	climate and watershed data	minutes	hillslope to watershed
KINEROS -AGWA	hydrology and erosion	X	X	Smith-Parlange	climate and geospatial parameter data	minutes-daily	hillslope to watershed data
RUSLE	erosion		X	SCS curve numbers	topography, soil erodibility, precipitation, practices	daily	hillslope
SPUR	hydrology, erosion on rangelands, plant production	X	X	SCS curve numbers, snow accumulation	topography, vegetation, precipitation, land use	daily	watershed and channel data
SWRRB	watershed hydrology, erosion and channel transport	X	X	modification of SCS curve numbers	climate and watershed, channel data	daily	small and large watersheds, channels
Stewart	hydrology, erosion, chemical transport	X		SCS curve numbers	precipitation, erodibility, and chemicals	daily	large and small watersheds
USDAHL	watershed hydrology		X	Holtan infiltration, subsurface drainage	climate, watershed and land use	minutes	hillslope and watershed data
WEPP	erosion and runoff	X	X	Green-Ampt	topography, land use and precipitation	minutes	hillslope practices

of long-term data collection at USDA experimental sites for understanding and predicting ecosystem dynamics, submitted to *Ecosystems*, 2007).

[37] Currently, rainfall, runoff, and sediment data collection continue, but data use has evolved to support several multiple government agencies, universities, and international research programs. These collaborative efforts are exemplified through interdisciplinary research campaigns, such as Monsoon '90 [*Kustas and Goodrich*, 1994], the Semi-Arid Land-Surface-Atmosphere (SALSA) Program [*Goodrich et al.*, 2000] and the Soil Moisture Experiments in 2004 (SMEX04) [*Jackson et al.*, 2008]. The extension of research from WGEW to the larger San Pedro River Basin has resulted in direct consultation with decision makers and elected officials and major contributions to larger research and monitoring networks.

[38] The Monsoon '90 Experiment, which ran from June through September 1990, initiated a new research focus on the use remote sensing to measure soil moisture, vegetation and evaporation to improve water and energy balance models (see special section in *Water Resources Research*, *30*, 1994). The evolving importance of global change in the early 90s further expanded SWRC research interests into the larger San Pedro River Basin (7610 km^2) that encompasses WGEW and extends into Mexico. The SALSA program was a collaborative effort among approximately 80 scientists from multiple government agencies, universities, and international research programs, co-led by the SWRC and the French Institut de Recherche pour le Développement (IRD), to conduct research in the Upper San Pedro River from 1995 to 2000. While the WGEW was specifically selected to isolate surface water from groundwater to focus research on runoff generation and its fate in ephemeral channels, the San Pedro Basin offers a good outdoor laboratory to investigate the impacts and potential feedbacks of global change in the context of local, state, and international water and ecology issues. The SALSA program addressed the research question "What are the consequences of natural and human induced changes on the water balance and ecological diversity of semiarid basins from individual events to decades"? Research conducted on the WGEW has, and continues to provide crucial information to support answering this question. A special issue of the *Journal of Agricultural and Forest Meteorology* (*105*, 2000) provides a summary of the SALSA program's results. The success of the SALSA program directly led to the membership of the USDA ARS and USGS and their research scientists in the Upper San Pedro Partnership, a consortium of 21 agencies and organizations working together to meet the water needs of area residents while protecting the San Pedro River.

[39] The more recent Soil Moisture Experiments 2004 (SMEX04) conducted for weeks in conjunction with the North American Monsoon Experiment (NAME) at WGEW addressed the development and evaluation of remotely sensed land surface products for terrestrial hydrology and soil moisture mapping. SMEX04 extended previous research funded by NASA Terrestrial Hydrology Program in catchments throughout North America (e.g., Iowa, SMEX02; Oklahoma, Alabama and Georgia, SMEX03). In addition to the science results (presented in a special issue of *Remote Sensing of Environment*, *112*, 2007), SMEX04 has also resulted in a data archive (http://nsidc.org/data/amsr_validation/soil_moisture/smex04/) and ongoing continuous measurements of soil moisture and associated parameters at WGEW (http://tucson.ars.ag.gov/dap/).

[40] Because of the success of interdisciplinary experiments at WGEW, the San Pedro Basin was recently selected as one of the first five basins in the world to be considered an operational Hydrology for the Environment, Life, and Policy (HELP) basin as part of a global initiative under the auspices of UNESCO and the World Meteorological Organization. The WGEW is also a critical shared research facility of the Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA) NSF Science and Technology Center (http://www.sahra.arizona.edu/), the Ameriflux network (http://public.ornl.gov/ameriflux/), the USDA Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN), (http://www.wcc.nrcs.usda.gov/scan/) and the National Atmospheric Deposition Program (NADP) network (http://nadp.sws.uiuc.edu). On the basis of the long-term hydrologic, climatic and image data, WGEW was chosen as one of 15 core sites worldwide by the International Community Earth Observing System (EOS) for satellite product validation and calibration (http://eospso.gsfc.nasa.gov/). Researchers from many universities and agencies around the world continue to conduct research within the WGEW, building on the exceptional knowledge base and research infrastructure provided by this unique hydrologic laboratory to further the mission of the SWRC to develop knowledge and technology to conserve water and soil in semiarid lands.

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