The Walnut Gulch Experimental Watershed - 50 years of watershed monitoring and research

MARY H. NICHOLS[1]

The United States Department of Agriculture - Agricultural Research Service - Walnut Gulch Experimental Watershed was established in 1953 with the broad objectives to 1) determine the effects of conservation projects on water yield and sediment movement and 2) quantify flood runoff from semi-arid rangeland watersheds. The 150 km^2 watershed was instrumented with raingauges and runoff measuring flumes arranged in a pattern of nested subwatersheds. Data collected during the past 50 years have been analyzed to characterize precipitation in convective thunderstorm dominated regions and to study and model subsequent flood wave movement, transmission losses, and water yield from complex watersheds. The effects of topography and various soil, vegetation, and surface cover complexes on water and sediment movements have been studied at spatial scales ranging from plots to watersheds. The initial research objectives have expanded to include remote sensing, nutrient cycling, and development of decision support systems. The comprehensive database has been used to characterize baseline conditions and variability inherent in semi-arid rainfall and runoff. The data have also been used to develop rainfall, runoff, and erosion prediction technologies. This chapter focuses on hydrologic and erosion research and includes a description of instrumentation and monitoring sites, a description of major research findings, and a summary of lessons learned from measurement and field experiences associated with both long-term and short-term projects.

Introduction

Soil erosion and land degradation across the United States (US) became a national crisis in the 1930s. Although the problems were serious, there was a lack of technology to address the problem, and a lack of basic data to develop new technology. In response, erosion control experiment stations and watershed research programmes were initiated to collect experimental data and develop new SWC (SWC) technologies. These data were needed to quantify rainfall, runoff, and erosion and to understand their relation to land management. In addition, erosion control demonstration projects were an important mechanism for transferring SWC information to land users and managers.

In the southwestern US, implementing upstream SWC programmes was problematic because of the potential affect on downstream water yields. Prior appropriation water laws existed in most of the western states in the US and a concern about reducing downstream water yield was paramount. The work of the Southwest Watershed Studies Group began July 1, 1951 with broad research objectives to determine if conservation practices would affect water yields and sediment movement and to evaluate flood runoff from semi-arid rangeland watersheds. The objectives were driven by fears among water users that range conservation work would deplete irrigation water supplies. In 1954, the research and personnel of the Southwest Watershed Studies Group were transferred to the newly formed United States Department of Agricultural (USDA) - Agricultural Research Service (ARS); and in 1961, the Southwest Rangeland Watershed Research Station was established with headquarters in Tucson. In the 1990s the name was changed to the Southwest Watershed Research Center (SWRC).

[1] Southwest Watershed Research Center, 2000 E Allen Rd., Tucson, AZ 85719, USA mnichols@tucson.ars.ag.gov

Today, nine scientists at the SWRC in Tucson, Arizona conduct research to understand and quantify semi-arid watershed processes and to develop technology for the sustainable management of natural resources. The mission of the SWRC is to understand and model the effects of changing climate, land use, and management practices on the hydrologic cycle, soil erosion processes, and watershed resources; to develop remote sensing technology and apply geospatial analysis techniques; to develop decision support tools for natural resource management; and to develop new technology to assess and predict the condition and sustainability of rangeland watersheds.

The objectives of this chapter are to 1) describe measurement and monitoring on the USDA-ARS Walnut Gulch Experimental Watershed, 2) describe major research findings and technology transfer, and 3) present an overview of monitoring lessons learned from 50 years of experimental research.

Measurement and Monitoring on the USDA-ARS Walnut Gulch Experimental Watershed

The Walnut Gulch Watershed was selected as a site for research by the USDA by a team of scientists and engineers (Renard and Nichols, 2003) who traveled throughout Arizona, New Mexico, and southern Colorado to examine, screen, and select watersheds suitable for long-term hydrologic, range management, and erosion research. Several criteria were developed for watershed selection with primary focus on the physical attributes of the watershed while incorporating the social impacts of the proposed research. Suitable research watersheds would range in size from 65 to 194 km^2 and would include a secondary tributary to a main channel that furnished irrigation water. The watersheds should receive 250-400 mm of annual precipitation. Vegetative cover would include range grasses (Blue grama,*Bouteloua gracilis;* Black grama, *B. eriopoda*; and their associates), with little or no cultivated land. Vegetative cover would not be deteriorated beyond recovery. The watershed would contain no closed basins, minimal water would be lost to deep percolation, and the watershed would be in a sediment producing area. Research efforts required that the sites be accessible during stormy weather and contain sufficient bedrock in the channel at or near the surface upon which to build gaging stations. The cooperation of ranchers within the area was a very important consideration in the selection of research watersheds. In addition, the chosen watersheds would be situated within a major drainage area in which controversy over water supplies existed or had the potential to develop. After investigating several locations, the team identified the Walnut Gulch Experimental Watershed (WGEW) in and adjacent to Tombstone, Arizona as the site to establish an intensively monitored research watershed (Fig. 1).

Monitoring objectives were clearly specified during initial planning of the WGEW with priority given to studying flood hydrology, which required measuring rainfall and runoff. Measurement methods and instrumentation were less clearly defined, because in the early 1950s very little was known about the spatial variability of air mass thunderstorm rainfall and the high velocity, short duration runoff events that characterize semi-arid regions. In addition, available instrumentation, including runoff gages and sediment samplers, were developed for monitoring perennial flow in humid climates and did not perform adequately in steep gradient ephemeral channels.

The WGEW is operated by the SWRC as an outdoor labouratory supporting multidisciplinary research with current research emphasis on hydrology, erosion and sedimentation, global climate change, CO_2 fluxes, remote sensing, and decision support systems. The long-term monitoring network at the WGEW is a critical component of research conducted by the SWRC.

The 150 km^2 WGEW (http://www.tucson.ars.ag.gov) is located in the semi-arid transition zone between the Sonoran and Chihuahuan Deserts in the Southwestern US. The main Walnut Gulch channel is a normally dry tributary to the San Pedro River. The San Pedro River, which originates in Sonora, Mexico and flows north into Arizona, is generally ephemeral with a perennial section associated with bedrock near the surface. Thunderstorm rainfall during the summer 'monsoon' season produces most of the surface runoff. Average annual precipitation on the WGEW ranges from 300 mm at the lower end (1,275 m asl) of the watershed to 340 mm at the upper end (1,585 m asl). Precipitation during July, August, and September accounts for approximately two-thirds of the annual total (Osborn, 1983; Nichols *et al.*, 2002), and results in nearly all of the surface runoff.

Core Monitoring Network

Work to instrument the WGEW began in 1953. Rainfall monitoring was initiated with 11 weighing bucket rain gauges distributed throughout the WGEW. Because of the limited aerial extent of thunderstorms, it quickly became apparent that the rain gauge network was inadequate to monitor spatially varied precipitation. Rain gauges were added to the network and today rain gauges are installed at 88 sites with a density of 1.7 rain gauges km^{-2}.

Operation, maintenance, data collection, and reduction associated with the original analog data-recording network at WGEW were costly and labour intensive. By the early 1990s, the mechanical rainfall and runoff sensors were becoming increasingly obsolete. In 1996, the SWRC began a multi-year effort to fully reinstrument the WGEW with electronic sensors and digital dataloggers. Each rain gauge consists of a weighing rain gauge retrofitted with a precision, temperature compensated load cell that outputs a voltage in response to the weight of water collected in the gage. Voltages are stored in a datalogger and are telemetered to the Tombstone field office every 24 hours. The electronics and dataloggers are stored in a metal cylinder below ground at each rain gauge. This offers the advantages of reducing vandalism and damage from lightning strikes, and helps to minimize temperature variations.

Measuring runoff and sediment in ephemeral alluvial channels is especially complex. Flows are infrequent, but reach high velocities and carry heavy sediment loads. Initially, options for measuring runoff were limited to structures such as V-notch weirs that were commonly used in perennial systems. However, on the WGEW conditions of highly variable flow with heavy sediment loads quickly filled behind weirs and in the throat of flumes resulting in the loss of hydraulic control through the measurement section. Several weirs and flumes on the WGEW failed or provided inadequate measurements, and new measurement structures needed to be designed. Following the initial structural failures at Walnut Gulch, a project was begun with personnel of the ARS Hydraulic Structures Laboratory in Stillwater, Oklahoma (Gwinn, 1964, 1970) to develop a new 'Walnut Gulch Supercritical-Flow Measuring Flume'. Based on the early field experiences and scale model work, supercritical flume designs evolved (Smith *et al.*, 1981) to measure the flow in 'flashy' ephemeral streams. Significant advances were made in developing measuring structures for high-velocity sediment-laden flows (Brakensiek *et al.*, 1979).

Within the WGEW, runoff monitoring stations were located according to a nested design so the relationship between the rainfall and runoff of successively larger subwatersheds could be analyzed. Runoff is monitored within the WGEW channel network upland, at the outlet of small watersheds (50-200 ha), and within upland subwatersheds (2-20 ha). From 1964 through 1967, 11 Walnut Gulch supercritical runoff-measuring flumes (Fig. 2) were constructed along the main stem of Walnut Gulch and major tributaries. There are also 10 instrumented stock ponds that collect water and sediment. These ponds are instrumented with stilling wells and floats to measure water depth, and periodic topographic surveys are completed to measure sediment accumulation. Four of the ponds have sharp crested weirs in the spillway to measure outflow. Based on the success of the Walnut Gulch supercritical flumes in the large channels, a small supercritical flume was designed, tested, and named the Santa Rita Critical Depth Flume. The Santa Rita Critical Depth Flume is widely used to measure runoff rates generally less than 2.8 $m^3\ sec^{-1}$. Runoff instruments have been upgraded and analog output is produced in parallel to a digital data stream at each measurement site. Water level recorders have been retrofitted with linear potentiometers and voltage outputs are stored in a datalogger and transmitted to the field office.

Sediment in channel runoff is sampled with a traversing slot sampler (Fig. 3) that was designed in response to limitations of alternative sampling methods (Renard *et al.*, 1986). When flow depth is greater than 0.06 m, the traversing slot travels across the outlet of the flume and diverts depth-integrated samples to evenly spaced, stationary slots below the flume exit. Water and particles smaller than the 13 mm slot are directed into sample bottles. The samples are dried and weighed to quantify sediment concentration.

Every 24 hours, each of the 125 instrumentation sites is automatically and sequentially contacted via radio. Stored data are transmitted to the Tombstone field office and the data are stored temporarily. Data are then transferred to the SWRC file server located in Tucson where the data are processed and archived.

In addition to the core rainfall, runoff, and sediment data, recent research focusing on global change and remote sensing has expanded the monitoring network to include meteorologic stations, carbon flux instruments, and soil moisture sensors. *As a result, the WGEW is the most highly instrumented semi-arid experimental watershed in the world. In addition, the WGEW has one of the largest published collections of satellite and aircraft based imagery with coordinated ground observation in the world.*

Research Findings and Technology Transfer

Fifty years of data collection, analysis, and interpretation have resulted in an extensive array of publications, research accomplishments, and technologies. A critical early accomplishment of work on the WGEW was the development of instruments to monitor the hydrologic and erosion cycle in semi-arid areas (Renard *et al.*, 1993). The need for specialized instrumentation led to the design and construction of the largest pre-calibrated structure for measuring runoff in semi-arid regions in the world. The precipitation and runoff monitoring network and the innovations and research results have allowed researchers to prepare a water balance for Walnut Gulch that is typical of semi-arid rangeland watersheds (Renard *et al.*, 1993). In addition to a general water balance, thunderstorm rainfall characteristics have been quantified and rainfall models have been developed (Osborn *et al.*, 1980; Osborn 1983). The temporally continuous, spatially distributed WGEW precipitation database was used to develop the first depth-area-intensity relationships for semi-arid convective airmass thunderstorms. Research to quantify the role and magnitude of transmission losses during runoff in ephemeral streams has resulted in simulation models that have been incorporated in watershed-scale runoff models (Lane, 1983).

SWRC scientists and data collected from the WGEW have played a critical role in the development and transfer of several national ARS simulation modelling efforts. Major contributions have been made to the development of RUSLE (Revised Universal Soil Loss Equation) (Renard *et al.*, 1991), CREAMS (A field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), EPIC (Erosion/Productivity Impact Calculator), SPUR (Simulation of Production and Utilization of Rangelands) (Hanson *et al.*, 1992), WEPP (Water Erosion Prediction Project) (Nearing and Lane, 1989; Laflen *et al.*, 1991), and KINEROS (Kinematic Runoff and Erosion Model) (Woolhiser *et al.*, 1990). Many of these models are being used outside of the US. These models are being used in combination with collected data to improve the scientific understanding of semi-arid watershed processes.

A range of research projects has been conducted during the last 50 years to improve the condition of deteriorating rangelands, and to improve SWC practices. In the late 1800s, the condition of rangelands in the southwest began to rapidly deteriorate in response to droughts and grazing pressure. Range renovation experiments conducted at the SWRC have resulted in new information on the relationship between grass seeding and precipitation patterns (Cox and Jordan, 1983), and mechanical and chemical treatments brush control (Cox *et al.*, 1983). Research projects to improve rangeland condition also resulted in the development and evaluation of land imprinting systems for brush management and seedling establishment (Dixon and Simanton, 1977). The land imprinting system consists of a conservation plow for imprinting land surfaces with complex geometric patterns. The land imprinter forms rainwater-irrigated seedbeds which help to ensure successful seed germination, seedling growth, and a subsequent cover of vegetation. Water harvesting research on the WGEW has contributed to technology used worldwide in arid and semi-arid areas. Research conducted to improve methods and materials for collecting and storing precipitation led to a stepwise guide for the design, selection of materials, installation, and maintenance of water-harvesting systems (Frasier and Myers, 1983). These larger scale applied research projects are complimented by plot-scale experiments to understand basic runoff and erosion processes.

An important research tool for conducting plot scale experiments is the rainfall simulator. Experiments designed at the WGEW using the rotating boom rainfall simulator have produced the world's largest database of rangeland hydrology and erosion measurements (Simanton *et al.*, 1986). The simulator is used to conduct experiments under controlled conditions. Rainfall, runoff, infiltration, and sediment measurements have been used for both basic process studies, and to develop, evaluate, and parameterize point-to-hillslope scale runoff and erosion models. Recently, a new computer-controlled variable intensity rainfall simulator, called the Walnut Gulch Rainfall Simulator, was developed to quantify the relationship between rainfall intensity and steady state infiltration (Paige *et al.,* 2003).

Monitoring Lessons Learned

Clearly, monitoring on the scale of the WGEW is well beyond the scope, scale, and objectives of most short-term projects. However, short-term monitoring should be conducted and interpreted in the context of available longer-term characteristics of rainfall and runoff. Collecting adequate data to evaluate soil conservation and watershed development projects in regions where extended periods of above or below average precipitation are the norm can take several years or even decades. As an example, an experiment in the 1970s on the WGEW to convert a shrub covered landscape to grass through ripping and seeding resulted in a short-term reduction in sediment yield, but rainfall during subsequent years was insufficient to establish the grasses in the longer term. The landscape is currently covered with shrubs and the short-term reduction in sediment yield has not significantly altered the long-term average sediment yield.

Data from long-term research programmes play a critical role in interpreting data collected as part of short-term monitoring and evaluation efforts by providing 1) baseline conditions against which to interpret, 2) temporal data from which variability can be quantified, and 3) a framework within which to develop and test new measurement methods. Data collected during short-term projects should be interpreted in the context of baseline conditions and temporal trends. In semi-arid regions the spatial variability of watershed characteristics such as soils, geology, drainage patterns, and cover can be dramatic over short distances, adding to the difficulty in developing general conclusions from individual project evaluations. Simulation models can be used to design conservation projects, as well as to design experiments. Modelling can be conducted prior to implementing field work to select sites for treatment, to select specific practices, and to understand the impacts of temporal and spatial variability in hydrologic and ecosystem variables on soil erosion.

Research experiments and the associated monitoring, measuring, and observations require enormous contributions of time, labour, and money. Access to the data beyond the life of an individual project will maximize the return on this investment. To ensure that future users have access to the data, it is important that thought be given to data management before data collection begins. Data management is a critical component of measuring and monitoring. An efficient data management system consists of a framework to store, organize, archive, and retrieve data associated with each project. Efficient access to quality controlled data allows a broader audience of users. In addition to the data, institutional knowledge becomes increasingly important as the length of data collection increases. Research programmes with long-term data collection histories face a significant challenge as institutional knowledge is lost through changes in personnel. A well designed database can be used to capture and store some of this knowledge.

Summary

The multidisciplinary research programme has addressed SWC in semi-arid regions by quantifying hydrologic and erosion processes, developing simulation models and decision support tools, and incorporating new technologies into research. Sufficient data to quantify the variability in semi-arid rainfall and runoff and their affect on water supply, water quality, and energy fluxes from rangeland watersheds requires a long-term monitoring programme. Such data are being used in combination with data collected to quantify upland and channel erosion and sedimentation processes to quantify landscape evolution patterns and the sustainability of rangeland ecosystems with respect to land use and management. The ecosystem responses of grass and shrub communities to short-term rainfall variability, as well as long-term changes in global climate are being evaluated. New technologies such as satellite based sensors to monitor temporal changes in forage production, soil moisture, and evaporation are being incorporated in the monitoring network. These core monitoring efforts are providing data for developing computer-aided decision-making tools that incorporate simulation models, databases, and expert opinion for improving semi-arid watershed management.

Long-term research programmes are critical to the conservation of semi-arid lands. A critical component of this research is instrumentation for monitoring, measuring, and collecting data. Data collected on the WGEW are of national and international importance and make up the most comprehensive semi-arid watershed dataset in the world. Research continues at the WGEW today in cooperation with local ranchers, federal agencies, universities, and international scientists interested in understanding semi-arid watersheds.

References

Brakensiek, D.L.; Osborn, H.B. and Rawls, W.J. (coordinators). 1979. *Field Manual for Research in Agricultural Hydrology.* USDA Agriculture Handbook 224. 500 pp.

Cox, J.R. and Jordan, G.L. 1983. Density and production of seeded range grasses in southeastern Arizona (1970-1982). *Journal of Range Management,* 36(5): 649-52.

Cox, J.R.; Morton, H.W.; LaBaume, J.T. and Renard, K.G. 1983. Reviving Arizona's rangelands. *Journal of SWC,* 38(4): 342-45.

Dixon, R.M. and Simanton, J.R. 1977. A land imprinter for revegetation of barren land areas through infiltration control. *Hydrology and Water Resources in Arizona and the Southwest.* Office of Arid Land Studies, University of Arizona, Tucson, 7: 79-88.

Frasier, G.W. and Myers, L.E. 1983. *Handbook of water harvesting.* USDA-ARS, Agriculture Handbook No. 600, 45 pp.

Gwinn, W.R. 1964. Walnut Gulch supercritical measuring flume. *Transactions of the American Society of Agricultural Engineers,* 10(3): 197-99.

Gwinn, W.R. 1970. Calibration of Walnut Gulch supercritical flumes. *Proceedings of the American Society of Civil Engineers,* 98(HY8): 1681-89.

Hanson, J.D.; Baker, B.B. and Bourbon, R.M. 1992. *SPUR II Model Description and User Guide:* GPSR Technical Report Number 1. USDA-ARS, Great Plains Systems Research Unit, Ft. Collins, Colorado.

Knisel, W.G. 1980. *CREAMS: A Field-scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems.* USDA Conservation Research Report No. 26, 640 pp.

Laflen, J.M.; Lane, L.J. and Foster, G.R. 1991. WEPP A new generation of erosion prediction technology. *Journal of SWC.* 46(1): 34-38.

Lane, L.J. 1983. *SCS National Engineering Handbook,* Section 4, Hydrology, Chapter 19: Transmission Losses. USDA-SCS, Washington, D.C, 32 pp.

Nearing, M.A. and Lane, L.J. 1989. *USDA Water Erosion Prediction Project: Hillslope Profile Model Documentation.* NSERL Report No. 2, USDA-ARS-NSERL, West Lafayette, IN.

Nichols, M.H.; Renard, K.G. and Osborn, H.B. 2002. Precipitation changes from 1956-1996 on the USDA-ARS Walnut Gulch Experimental Watershed. *Journal of the American Water Resources Association,* 38(1): 161-72.

Osborn, H.B. 1983. *Precipitation Characteristics Affecting Hydrologic Response of Southwestern Rangelands.* USDA-ARS Agricultural Reviews and Manuals: ARM-W-34, January.

Paige, G. B.; Stone, J. J.; Smith, J. R. and Kennedy, J.R. 2003. The Walnut Gulch Rainfall Simulator: A Computer-Controlled Variable Intensity Rainfall Simulator. *Applied Engineering in Agriculture*, 20(1): 1-7.

Renard, K.G.; Simanton, J.R. and Fancher, C.E. 1986. Small watershed automatic water quality sampler. *Proceedings of the 4th Federal Interagency Sedimentation Conference, Las Vegas, NV* Vol. 1, pp. 51 to 58.

Renard, K.G.; Foster, G.R.; Weesies, G.A. and Porter, J.P. 1991. RUSLE Revised Universal Soil Loss Equation. *Journal of SWC,* 46(1): 30-33.

Renard, K.G.; Lane, L.J.; Simanton, J.R.; Emmerich, W.A.; Stone, J.J.; Weltz, M.A.; Goodrich, D.C and Yakowitz, D.S. 1993. Agricultural Impacts in an Arid Environment: Walnut Gulch Studies. *Hydrologic Science & Technology,* 8(1-4): 145-90.

Renard, K.G. and Nichols, M.H. 2003. History of small watershed research in non-forested watersheds in Arizona and New Mexico. *Proceedings of the 1st Interagency Conference on Research in the Watersheds,* October 27-30, 2003 Benson, AZ, pp. 296-301.

Simanton, J.R.; Johnson, C.W.; Nyhan, J.W. and Romney, E.M. 1986. Rainfall simulation on rangeland erosion plots. In: L.J. Lane (ed.), Erosion on Rangelands: Emerging Technology and Data Base. *Proceedings of the Rainfall Simulator Workshop,* Jan 14-15, 1985, Tucson, Arizona. Pp. 11-17. Society for Range Management, Denver, CO.

Smith, R,E.; Chery, D.L.; Renard, K.G. and Gwinn, W.R. 1981. *Supercritical Flow Flumes for Measuring Sediment Laden Flow.* USDA-ARS Technical Bulletin No. 1655, 72 pp.

Woolhiser, D.A.; Smith, R.E. and Goodrich, D.C. 1990. *KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual,* USDA-ARS, ARS-77, 130 pp.

Figure 1. USDA-ARS Walnut Gulch Experimental Watershed location map.

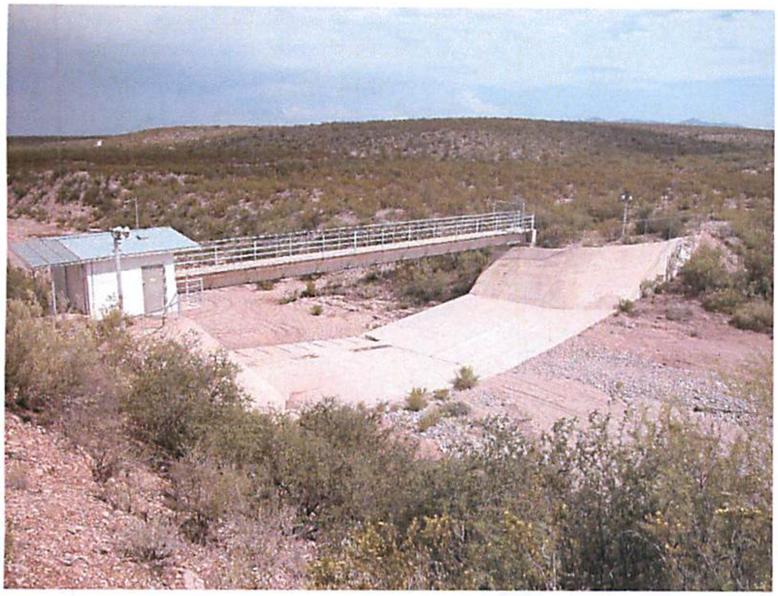

Figure 2. Walnut Gulch supercritical runoff measuring flume.

Figure 3. Santa Rita critical depth flume and traversing slot sediment sampler.