Instrumentation and research at the USDA-ARS Walnut Gulch Experimental Watershed

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The United States Department of Agriculture - Agricultural Research Service Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona, USA, has served as an outdoor laboratory for the study of semiarid hydrology, erosion and sedimentation since the 1950s. Hydraulic structures along the large watershed channels, a dense raingage network, and intensively monitored watersheds have yielded a unique database for analyzing and interpreting rainfall, runoff, and erosion processes on semiarid lands. The monitoring program has evolved in response to changes in measurement technology as well as to changes in research scope. The research program at the WGEW has been expanded to include meteorologic, soil chemistry, remote sensing, soil moisture, and carbon flux measurements. In celebration of the 50th anniversary of the WGEW, The First Interagency Conference on Research in the Watersheds (ICRW) was held in Benson, Arizona in October of 2003. The conference was a forum for information exchange among researchers working at the watershed scale and stakeholders working on watersheds. This paper describes instrumentation and monitoring on the WGEW beginning with a historical perspective of the ARS watershed research network and site selection followed by an overview of the challenges associated with instrumenting a semiarid watershed. Initial challenges associated with establishing the core rainfall and runoff networks, the evolution of instrumentation, and current data management challenges are described. In addition, a summary of the ICRW meeting is presented.

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Introduction

Water has been, and continues to be, a critical factor in land use, management, and development in the semiarid Southwest. Watershed research to address water quantity and quality and to support conservation programs in the United States has a long history. As early as the 1930's, efforts were underway to establish research programs and experimental watersheds to better understand hydrologic and erosion processes. The sustainable use of soil and water resources required basic information upon which to make sound policy and management decisions.

During the late 1800s and early 1900s land degradation in southwestern US resulting from intense grazing of fragile vegetation and on occasion plowing of sod prairies often led to excessive erosion. However, relatively little data were available to approach the problem from a scientific point of view and most of the data that were available to study rangeland erosion were derived from plot scale studies. There was a general lack of data to understand watershed scale hydrologic and erosion processes and to develop solutions to land degradation in the arid and semiarid areas of the southwestern US.

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 semiarid rangeland watersheds. The objectives were driven by fears among water users that range conservation work would deplete irrigation water supplies. Water yield was a critical concern because prior appropriation water laws were in effect throughout much of the western US and upland soil-conservation practices had the potential to minimize erosion and alter the distribution of surface water.

In 1954, the research and personnel of the Southwest Watershed Studies Group were transferred to the newly formed Agricultural Research Service; and in 1961, the Southwest Watershed Research Station was established with headquarters in Tucson. Today, nine scientists at the Southwest Watershed Research Center (SWRC) in Tucson, Arizona conduct research to understand and quantify semiarid 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 SWRC operates the Walnut Gulch Experimental Watershed (WGEW), surrounding the town of Tombstone, Arizona, as an outdoor laboratory supporting multidisciplinary research with emphasis on hydrology, erosion and sedimentation, and remote sensing. Research is conducted

in cooperation with the Natural Resource Conservation Service, the local Soil Conservation Districts, and the ranchers who own or manage the land of the watersheds.

Research Watershed Site Selection

The Walnut Gulch Watershed was selected following an extensive site search. Several criteria were developed for watershed selection with primary focus on the physical attributes of the watershed while incorporating the social impacts of proposed research. From August 1951 to June 1952, a team of scientists and engineers (engineer, geologist, soil scientists, and range scientist), in cooperation with local Soil Conservation Service personnel and staff specialists, traveled throughout Arizona, New Mexico, and southern Colorado to examine, screen, and select watersheds suitable for long-term hydrologic, range management, and erosion research.

Suitable research watersheds would range in size from 25 to 75 sq. mi (65 to 194 sq. km) and would include a secondary tributary to a main channel that furnished irrigation water. The watersheds would receive 10 – 16 inches (254 – 406 mm) of precipitation annually. Vegetative cover would include range grasses (Blue grama [*Bouteloua gracilis*], Black grama [*Bouteloua 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, and no water would be lost to deep percolation, and the watershed should be in a sediment producing area. Anticipated research projects 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 runoff gaging stations.

The cooperation of ranchers within the area was a very important consideration in the selection of locations for research watersheds. In addition, the chosen watersheds were 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 Upper Alamogordo Creek east of Santa Rosa, New Mexico and the Walnut Gulch Watershed surrounding the town of Tombstone, Arizona for study. The Walnut Gulch Experimental Watershed is part of the national ARS network of 17 locations where data are collected on 140 subwatersheds (Weltz and Bucks 2003).

Walnut Gulch Experimental Watershed

The 58 sq. mi (150 sq. km) Walnut Gulch Experimental Watershed (http://www.tucson.ars.ag.gov) is located in the semiarid transition zone between the Sonoran and Chihuahuan Deserts (Figure 1). The main Walnut Gulch channel drains to the west into the San Pedro River near Fairbanks, Arizona. The San Pedro River, which heads in Sonora, Mexico and flows north into Arizona, is generally ephemeral with a perennial section associated with bedrock near the surface. Flow events in response to thunderstorm rainfall dominate the runoff regime. Average annual precipitation on the WGEW ranges from 300 mm (11.8 in) at the lower end (1275 m) of the watershed to 340 mm (13.4 in) at the upper end (1585 m). Precipitation during July, August, and September accounts for approximately 2/3 of the annual total (Osborn

1983; Nichols et al. 2002), and results in nearly all of the surface runoff. These facts, unfortunately, were unknown when efforts to instrument the watershed were initiated.

Among the first major work objectives on the WGEW were to 1) install and operate a network of raingages and 2) develop and construct runoff-measuring devices. Instruments were generally available to measure rainfall and runoff in humid areas, but were extremely limited for the unique hydrologic characteristics of semiarid watersheds. In the semiarid southwestern US precipitation is highly spatially varied, runoff is flashy and inconsistent, and heavy sediment loads confound runoff measurement. As will be seen, data collection was often complicated by attempts to apply measurement technology and methods developed in humid areas to semiarid regions.

Early Instrumentation Challenges

The challenge of building a measurement network was tackled by an interdisciplinary team of engineers and scientists. Initial instrumentation efforts were directed toward collecting flood hydrology data, specifically measuring rainfall and runoff. The climate of southeastern Arizona presented several challenges. How many gages would be required to measure the spatially and temporally variable thunderstorm rainfall? In 1954, ten gages had been distributed over the area, and gages were being added as rapidly as possible. Measurement of runoff when no precipitation was recorded was evidence that the raingage network was not dense enough. The original network was designed with a density of 1 gage per square mile (2.5 sq. km).

The backbone of the precipitation data collection network at Walnut Gulch is the Belfort weighing raingage. Analogue data are collected through a pen trace on a rotating drum driven by a hand wound clock. The maintenance, repair, and servicing required a dedicated team of field technicians and a jeweler trained in clock repair. In addition to the labor-intensive field support, data retrieval required digitizing the charts, and populating a database that requires additional processing for quality assurance and control, and reducing the data to common hydrologic measurement units.

Measuring runoff and sediment in ephemeral alluvial channels is especially complex. Options for measuring runoff included V-notch weirs and flumes, which were commonly used in perennial systems. However, conditions of highly variable flow with heavy sediment and debris loads quickly filled behind weirs (Figure 2) and in the throat of flumes resulting in the loss of hydraulic control through the measurement section. A modified "critical-depth" flume was the best option for measuring sediment-laden runoff.

During 1953, 5 large trapezoidal critical depth runoff-measuring flumes were constructed. By July 1, 1954, the hydraulic sections of 5 flumes (table 1) were completed with design capacities ranging from 1500 to 8000 cfs (43 to 227 cms). A sequence of significant storms started runoff that began in late July 1954 and continued with generally not more than 24-hour interruption within the watershed until late August. By the end of the season only 1 flume remained intact and operational (Figure 3). The structures failed because they were a) hydrologically undersized, b) hydraulically inadequate, and c) structurally incapable to withstand the loads involved.

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; Gwinn 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).

From 1964 through 1967, eleven Walnut Gulch supercritical-flow measuring flumes (Figure 4) were constructed along the main stem of Walnut Gulch and major tributaries. The maximum design capacity of the largest flume at the watershed outlet is 22,500 cfs (637 cms). Sediment sampling programs were initiated following flume construction. Suspended sediment samples were collected at Flumes 1 and 6 using a DH48 and/or P61 samplers from 1970 – 1980 during storm events when personnel were available. The large-flume sediment-sampling program was halted in the early 1980's due to safety concerns, as well as personnel and budget limitations.

In 1973, a concrete footbridge was installed across Flume 6 at the location of the runoff measurement section (Figure 5). The bridge currently provides access and a site for mounting instrumentation and sensors. Runoff in the main Walnut Gulch channel consists of an average of 11 events per year since 1957 (range of 1 to 22 events per year) at Flume 1 and 12 events per year since 1962 at Flume 6 (range of 2 – 28 events per year).

The initial plan for instrumenting the watershed called for a nested arrangement of measurement sites. Data collection in smaller, upland watersheds and at the outlets of interior watersheds are critical for understanding spatially varied hydrologic and erosion processes (Figure 6).

Based on the success of the Walnut Gulch Supercritical Flumes in the large channels, a small supercritical flume was designed and named the Santa Rita Critical Depth Flume (Figure 7). The Santa Rita Critical Depth Flume is widely used to measure runoff rates generally less than 2.8 cms (100 cfs). A traversing slot sediment sampler was designed in response to limitations of alternative sampling methods (Renard et al. 1986). When flow depth is greater than 0.06 m (2.4 in), 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 (0.5 in) slot are directed into sample bottles. The samples are dried and weighed to quantify concentration of fine sediment. Particles larger than the slot width pass through the flume and are not collected. Santa Rita Critical Depth Flumes and traversing slot samplers are currently operating in the Lucky Hills intensive study area within the WGEW.

The evolution of instrumentation

Operation, maintenance, data collection, and reduction associated with the analog data-recording network at WGEW are costly and labor 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 re-instrument the WGEW with electronic sensors and digital data-loggers. These updated technologies were coupled with radio telemetry to remotely transmit recorded data to a central computer. This effort has greatly reduced operational overhead by reducing labor, maintenance, and data processing time.

Currently, there are 125 core instrument installations on the WGEW. Two intensive study sites, one characterized by grass cover (2 small watersheds), and one characterized by brush cover (6 small watersheds) are monitored with meteorological, soil moisture and temperature and energy flux measurements. Runoff is measured at the outlet of each small watershed, and sediment samples are collected during runoff. There are 10 stock pond watersheds instrumented with stilling wells containing floats to measure inflow depth. Four of the ponds have sharp-crested weirs in the spillways for measuring outflow. Sediment accumulation is measured in the ponds by conducting a topographic survey of the pond surface using a total station. A total of 11 large flumes along the main watershed channels are used to measure runoff (Figure 6).

Precipitation is measured at 88 sites throughout the watershed, with a density of 1.7 gages per sq. km (0.7 per sq. mi). A high resolution, self contained, simple raingage was designed by WGEW field technicians and has been tested under simulated and natural rainfall conditions. The gage consists of a precision, temperature compensated load cell, which measures the weight of a platform-mounted container that collects water during a precipitation event. As water accumulates in the container, the voltage output from the load cell changes. The programmed datalogger samples voltage every second and averages at 1 minute interval. To minimize data storage requirements and transmission time, only time stamps and voltages commensurate with precipitation detectable to 0.25mm (0.01 in) precision are recorded. The capacity of the raingage is 200mm (8 in) before it must be serviced. A very unique feature of the raingage design is that all electronics, data logger, and radio/modem components are housed in a metal below-ground cylinder, thus reducing vandalism, lightning interference, and temperature effects.

The conversion from analog to digital output at runoff measuring flumes was accomplished by attaching a precision linear potentiometer to the output gear shaft of the water-level recorders. The voltage output from the potentiometer is collected by a data logger which averages 1-second samples at 1-minute intervals and records flow data (time stamp and voltage) only when a minimum depth threshold has been exceeded (0.003m (0.12 in) at small flumes, 0.015m (0.59 in) at large flumes and stock tanks). At sites where automatic sediment sampling is done, the data logger controls the operation of the sampler and records each sample's begin time and total time to collect the sample. Samples are collected when flow depth is greater than 0.06m (2.36 in).

On a daily basis, instruments are automatically and sequentially queried and data are transmitted to a dedicated computer at the Tombstone field office. Data are archived, used to generate daily reports, and written to the SWRC network server in Tucson via a 56K phone line. Daily data radio transmission time and file size can range from a minimum of 1.5 hour and 300 KB for non-event days to over 4 hours and 1MB for a day on which rainfall and runoff occurred.

Data collected on the WGEW are considered experimental data. Historically, ARS watershed data have not been collected, processed, and reviewed under a national set of standards. The primary data users were research scientists. Beginning in 2001, the SWRC undertook an effort to provide data access to an expanded group of users. This effort generally consists of 2 major components: 1) data integrity, and 2) data management system. New procedures for processing and checking the electronic data have been developed. The SWRC data management system was developed to provide a framework for storing, organizing, archiving, and retrieving data

associated with SWRC research. The goals of the data system are 1) to promote analyses and interpretations of data by improving access and 2) to meet our obligation to make data available to the public.

The data management system consists of a website, which provides an interface to the data, and a MS SQL Server relational database, which is used to process, store, and manage data. The database and website were designed by SWRC staff, who also wrote the data processing code. Data can be accessed over the Internet at http://tucson.ars.ag.gov/dap/. The system was released to the public in October 2003, and since that time the online data access website has received more than 1000 visitors.

The First Interagency Conference on Research in the Watersheds

The First Interagency Conference on Research in the Watersheds (ICRW) was conceived by a group of federal agencies (ARS, USGS, USFS, BLM, EPA, NRCS and NSF) to bring together researchers working at the watershed scale and stakeholders working on watersheds to bridge the gap between the two groups. The intent was to have researchers present what they are doing now, what more they could do, and how the research is being applied for management purposes. In turn, the watershed stakeholders would articulate how current research is helping them and the additional steps that are needed to help them make better decisions about managing their watersheds. The meeting organizers specifically designed this conference to be a one-stop shopping point for stakeholders to get a comprehensive overview of watershed research by all of the major federal agencies conducting watershed research.

To achieve these goals, the format of ICRW was unique. First, the conference was located at a small facility within the San Pedro River Watershed in the town of Benson, Arizona. All meals were catered on site to encourage informal interaction between researchers and stakeholders. Second, the first plenary session consisted of invited speakers from federal agencies to review their watershed research programs and from the Upper San Pedro Partnership to present an example of research scientists and decision makers working together. This set the stage for the nearly 150 volunteered presentations of research on watershed-scale topics such as hydrology, erosion, water quality, economics, instrumentation, ecology, sociology, remote sensing and fire. Third, the ICRW was scheduled to coincide with the 50th anniversary of the USDA ARS Walnut Gulch Experimental Watershed. To celebrate 50 years of research at this experimental watershed, a half-day field tour and evening BBQ at the watershed were scheduled.

The ICRW proceedings begins with six invited papers describing the current and future watershed research programs of ARS, USGS, USFS, BLM, EPA and CUAHSI. Following these, the proceedings provide an overview of watershed research organized by the topics of erosion, hydrology, watershed modeling, watershed networks and data management, water quality and quantity, ecology, integrated management and integrating science with watershed decision making.

Research Accomplishments

The Walnut Gulch Experimental Watershed is critical to the success of scientists in quantifying semiarid hydrologic and erosion processes. Research has resulted in the first quantification of transmission losses in ephemeral channels, the first depth-area-intensity relationships for semiarid convective airmass thunderstorms, and the development of simulation models such as RUSLE and KINEROS. Experiments designed at the WGEW using the rotating boom rainfall simulator have produced the world's largest database of rangeland hydrology and erosion measurements. The need for specialized instrumentation led to the design and construction of the largest pre-calibrated structure for measuring runoff in semiarid regions in the world, and the most highly instrumented semiarid experimental watershed in the world. WGEW research has contributed to water harvesting technology worldwide, as well as the development of land imprinting systems for both brush management and seedling establishment.

In response to evolving technologies and user needs, the SWRC research program has expanded to include remote sensing, decision support systems, and global climate change and carbon fluxes. The WGEW has one of the largest published collections of satellite and aircraft based imagery with coordinated ground observation in the world.

Summary

Long-term research programs are critical to the conservation of semiarid lands. A critical component of this research is instrumentation for monitoring, measuring, and collecting data. Data collected on the Walnut Gulch Experimental Watershed are of national and international importance and make up the most comprehensive semiarid watershed dataset in the world. Research continues at the WGEW today in cooperation with NRCS, NRCDs, local ranchers, Universities, and international scientists interested in understanding semiarid watersheds.

References

Brakensiek, D.L., H.B. Osborn, and W.J. Rawls (coordinators). 1979. Field manual for research in agricultural hydrology. U.S. Dept. Agric., Agriculture Handbook 224. 500pgs.

Gwinn, W.R. 1964. Walnut Gulch supercritical measuring flume. Trans. Am. Soc. Agric Engrs. 10(3):197-199.

Gwinn, W.R. 1970. Calibration of Walnut Gulch supercritical flumes. Proc. Am. Soc. Civil Engrs. 98(HY8):1681-1689.

Nichols, M.H., Renard, K.G., Osborn, H.B. 2002. Precipitation changes from 1956-1996 on the USDA-ARS Walnut Gulch Experimental Watershed. J. Am. Water Resources Assoc. 38(1):161-172.

Osborn, H.B. 1983. Precipitation characteristics affecting hydrologic response of southwestern rangelands. USDA-ARS Agricultural Reviews and Manuals: ARM-W-34, January.

Renard, K.G., J.R. Simanton, and C.E. Fancher. 1986. Small watershed automatic water quality sampler. Proc. 4th Federal Interagency Sedimentation Conference, Las Vegas, NV Vol1, pp 1-51 to 1-58.

Smith, R,E., D.L. Chery, K.G. Renard, and W.R. Gwinn.1981. Supercritical flow flumes for measuring sediment laden flow. USDA-ARS Technical Bulletin #1655, 72 pgs.

Weltz, M. A. and D. A. Bucks. 2003. The USDA-Agricultural Research Service Watershed Research Program. Proc. 1st Interagency Conf. on Research in the Watersheds, Oct. 27-30, Benson, AZ, pp. 2-8.

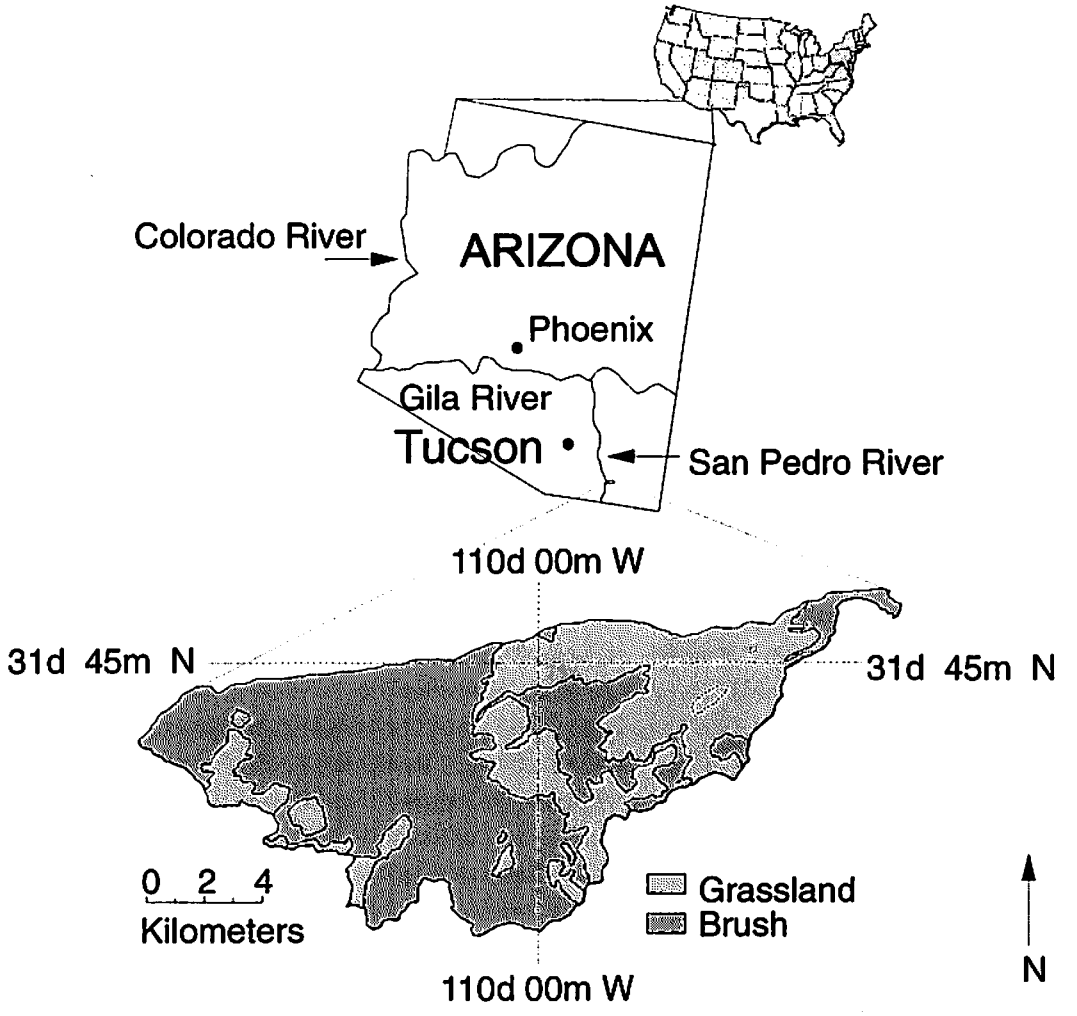

Figure 1. USDA-ARS Walnut Gulch Experimental Watershed location map

Figure 2. V-notch weir with loss of hydraulic control at the measuring section caused by sediment deposition

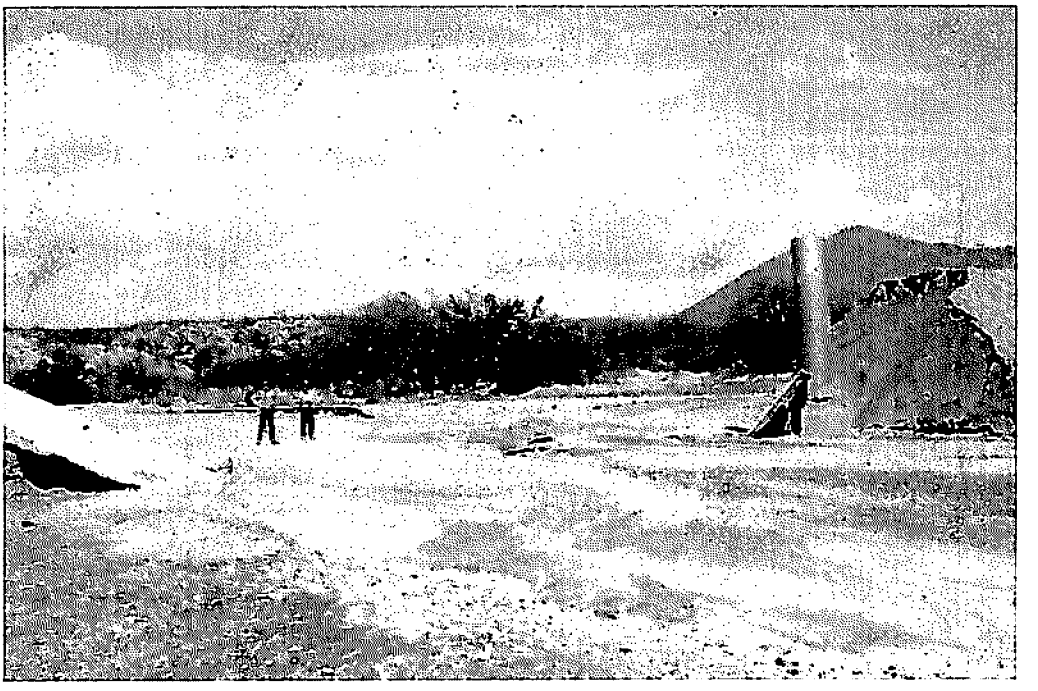

Figure 3. Failed runoff measuring flume in the main Walnut Gulch channel

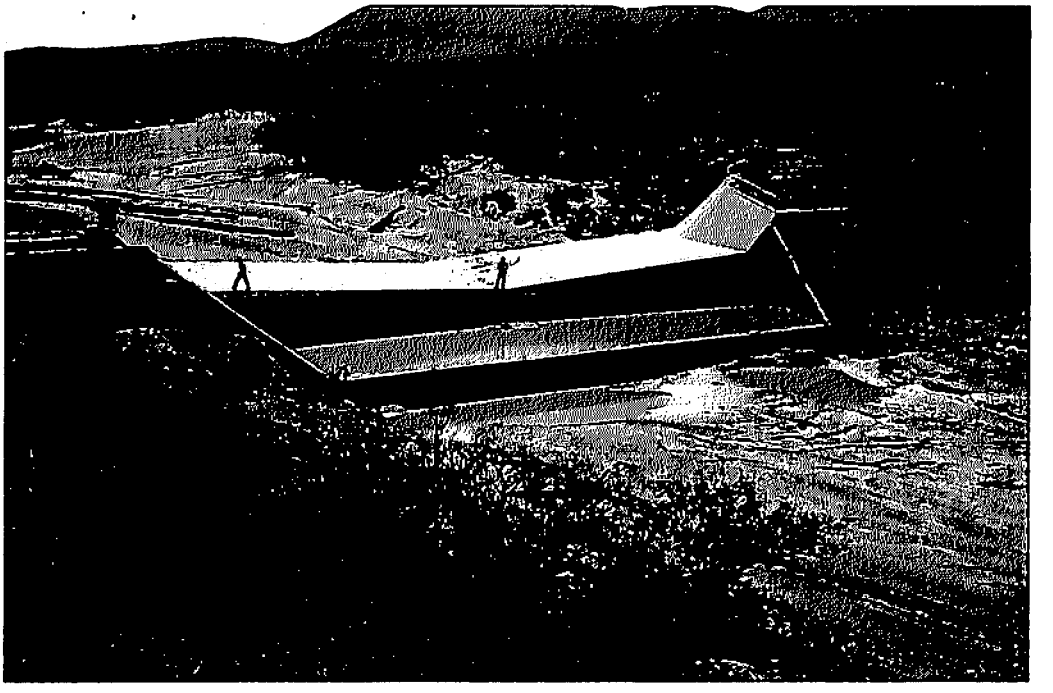

Figure 4. Walnut Gulch Supercritical Flow Measuring Flume Number 1 at the outlet of the WGEW

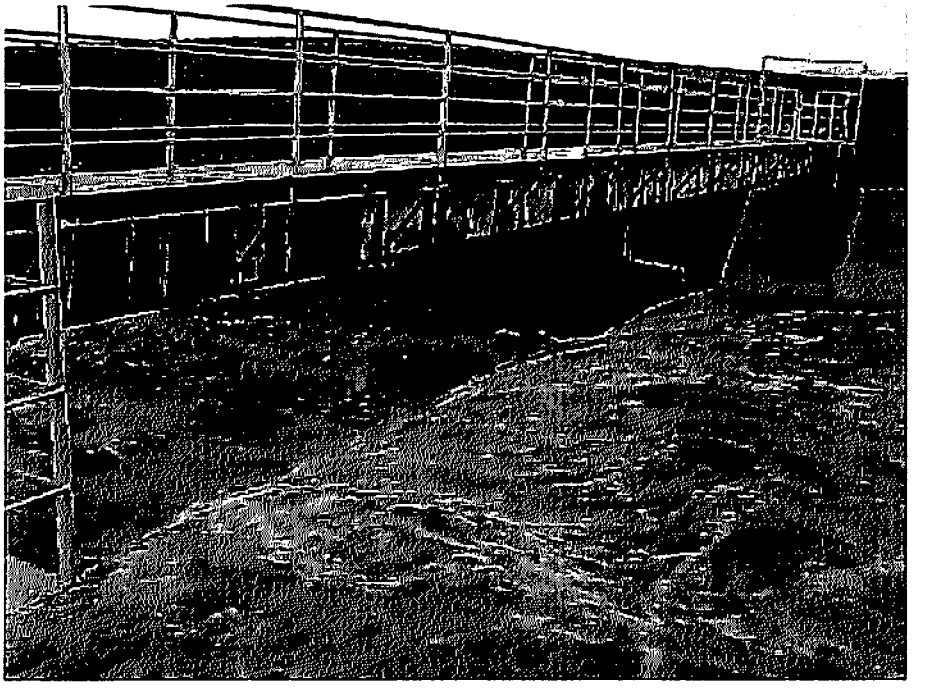

Figure 5. Walnut Gulch Experimental Watershed Flume 6 with footbridge and sensor mount

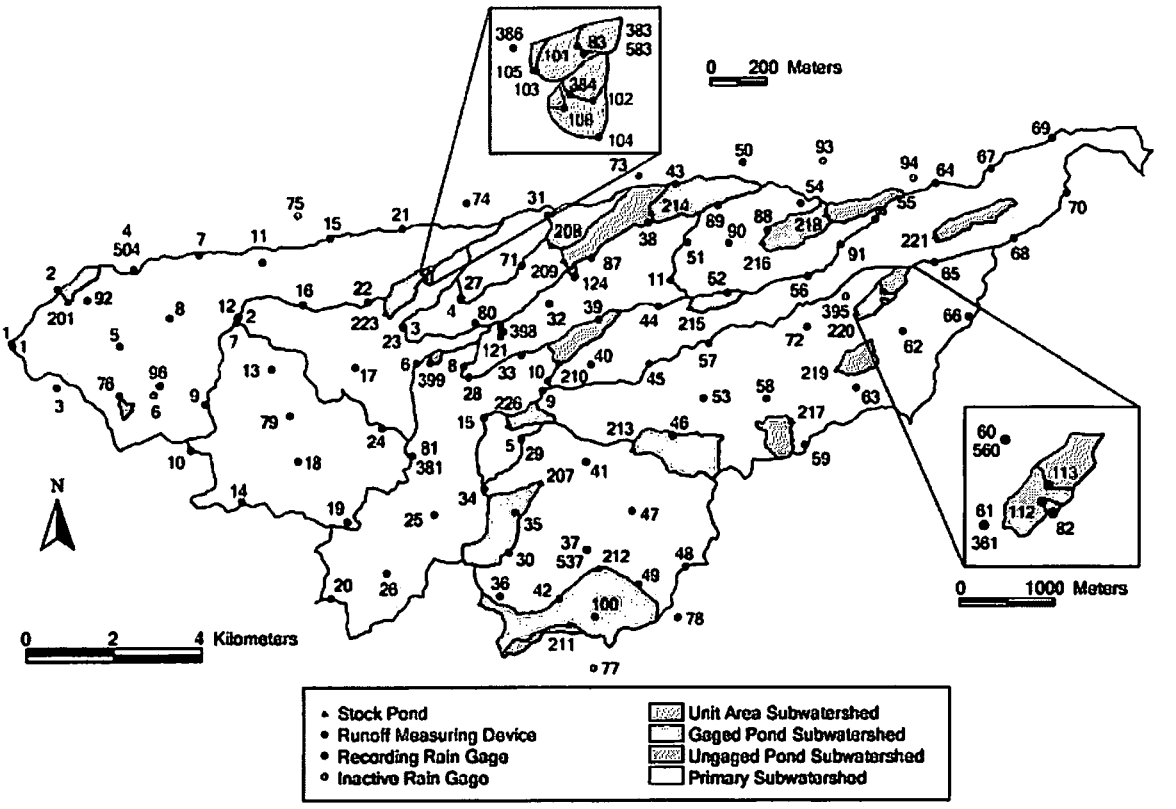

Figure 6. Walnut Gulch Experimental Watershed instrumentation map

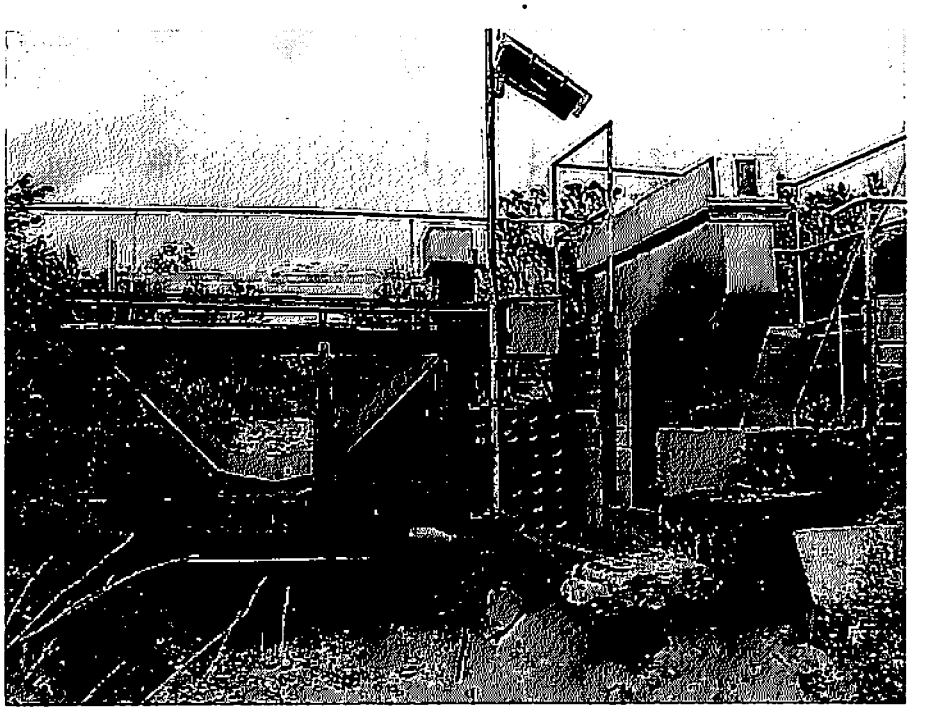

Figure 7. Santa Rita Critical Depth Flume and traversing slot sediment sampler

Table 1. Summary of Large Flume Construction on the Walnut Gulch Experimental Watershed

Flume	Year built	Discharge Area		Capacity		Start of Runoff Record	Notes*
		mi^2	km^2	ft^3/s	m^3/s		
1	1954	57.66	149.3	8000	227	4/8/1954	Original Supercritical Flume
1	1964	57.66	149.3	22,500	637	4/1/1964	Walnut Gulch Supercritical Flume
2	1953	43.91	113.7	8000	227	9/16/1953	
2	1959	43.91	113.7	18500	524	1959	Walnut Gulch Supercritical Flume
3	1954	3.47	9.0	3000	85	6/1/1954	
3	1958	3.47	9.0	6000	170	6/1/1958	Walnut Gulch Supercritical Flume
4	1954	0.88	2.3	2000	57	7/13/1954	
4	1969	0.88	2.3	1500	42	1969	Walnut Gulch Supercritical Flume
5	1954	8.61	22.3	1200	34	7/12/1954	Original Supercritical Flume, decommissioned in 1973
6	1962	36.72	95.1	15000	425	7/4/1962	Walnut Gulch Supercritical Flume Footbridge added 1973
7	1966	5.22	13.5	8000	227	1966	Walnut Gulch Supercritical Flume
8	1963	5.98	15.5	8000	227	8/31/1963	Walnut Gulch Supercritical Flume
9	1967	9.11	23.6	9500	269	5/26/1967	Walnut Gulch Supercritical Flume
10	1967	6.42	16.6	8000	227	6/13/1967	Walnut Gulch Supercritical Flume
11	1963	3.18	8.2	6000	170	3/1/1963	Walnut Gulch Supercritical Flume
15	1965	9.24	23.9	1200	34	6/15/1965	Walnut Gulch Supercritical Flume

* Flume details can be found in Smith et al. 1981; Gwinn 1964; Gwinn 1970.