Southwest Watershed Research Center

USDA Agricultural Research Service

MISSION STATEMENT

To develop new knowledge and technology through excellence in research to serve ARS and the public by providing the scientific basis for sustainable natural resources and a quality environment in support of agriculture. We seek to accomplish our mission through research in five major program areas: Basic Hydrology, Erosion and Sedimentation, Global Climate Change, Water Quality, and in cooperation with Mexico, Sustainable Natural Resources Research. Major research objectives are:

- to quantify the hydrologic cycle and the role of time and space scales to understand and accurately model hydrologic processes in arid areas,

- to develop natural resource models incorporating erosion and sedimentation prediction models,

- to separate the influences of natural variations from anthropogenic sources on global climate change and to determine the impact of possible global changes on water supplies and quality, soil and vegetative resources,

- to develop decision support systems for water quality and natural resource models, and

- to conduct cooperative research with Mexico to develop conservation management systems for sustainable natural resources in agriculture.

PROGRAM

Research involves developing fundamental scientific principles, laboratory and field data bases, and computer simulation models with emphasis on using the developed technology to transfer research results, data, and understanding to land managers and decision makers in the public and private sectors. Center research supports several national technology development/transfer projects including the USDA Water Erosion Prediction Project (WEPP), the Revised Universal Soil Loss Equation (RUSLE) project, the USDA Water Quality Initiative, the ARS Global Change Program, and the US-MEXICO Binational Sustainable Natural Resources Research project. We also seek to disseminate our research results and data to other research scientists in similar and related disciplines. The Center operates the world renowned Walnut Gulch Experimental Watershed near Tombstone, AZ and operates eight small experimental watersheds on the Santa Rita Experimental Range near Tucson, AZ.

SCIENTIFIC STAFF

The research team includes hydraulic engineers, hydrologists, systems engineers, and soil scientists. Research is conducted in active cooperation with other federal, state and local agencies, universities, national and international research organizations, and private individuals.

HISTORICAL CHANGES, RANGELANDS OF THE SOUTHWEST

Personnel

T. N. Johnsen, Jr. (collaborator), K. G. Renard (collaborator) and L. J. Lane

Southwestern America is centered around Arizona and New Mexico, but includes parts of Texas, Nevada, California, and the Mexican States of Baja California del Norte, Sonora, and Chihuahua (Brown, 1982). Deserts, grasslands, or shrublands, which developed during the last 8,000 to 11,000 years following the last ice age, cover about 80% of the region. Native large grazing animals disappeared from the area about 5,000 years ago.

Domesticated livestock were introduced into the region by Spanish explorers and settlers in the 1500's (Wagner, 1952). Between 1697 and 1740, Father Kino established missions and distributed small herds of cattle and sheep throughout Chihuahua and Sonora, Mexico, southeastern AZ, southern NM, and west Texas. The Spanish herded cattle in these areas between 1770 and 1827, but were frequently forced to retreat south by warring Indians, malaria, and drought. Prior to the Civil War, American botanists, military personnel, and religious groups traveling through the region noted sacaton, alkali sacaton, and tabosa lowlands and grama grass uplands. Brushy species such as mesquite, catclaw, white_thorn, creosotebush and tarbush were present, but their numbers were limited (Hastings and Turner, 1965). The Santa Cruz Valley, between Nogales and Tucson, AZ, was described by Bartlett in 1854 (Humphrey, 1958): "we were off this morning (from Tucson)... and soon entered a thickly wooded valley of mezquit [mesquite]. A ride of nine miles brought us to San Xavier del Bac... a mile farther, and stopped in a fine grove of large mezquit [mesquite] trees near the river, where there was plenty of grass." Also, according to Reid in 1858 (Humphrey, 1958), "The bottoms (between San Xavier and Tubac) in places were several miles wide ...covered with tall, golden colored grass (big sacaton grass)...divided by a meandering stream a dozen yards wide and as many inches deep, this shaded by cottonwood, willows and mezquits [mesquites]."

It has been estimated that range cattle in the desert southwest exceeded 500,000 head between 1830 and 1840. After the Civil War, additional cattle were either driven or shipped from eastern TX, central Mexico, and the Great Basin. Populations peaked around 1.5 million head on southeast Arizona ranges in 1893 (Humphrey, 1958). Ranchers H. C. Hooker and C. H. Bayless described the events which took place between 1870 and 1901: "...trappers exterminated the beaver, farmers plowed the sacaton bottoms, rivers were channeled to provide irrigation for crops, and ranchers over-grazed the grasslands." An extended drought occurred in the early 1890's, water sources dried up and approximately 65% of the range cattle died. The drought was over by 1895, but the combined effects of overgrazing, farming, drought, excessive hay harvesting, and flooding had resulted in accelerated sheet and gully erosion. Today, the Santa Cruz Valley, between Nogales and Tucson, described by Bartlett in 1854, is typified by a channel 95 km (60 mi) long and about 9.5 m (30 ft) wide and 6.1 m (20 ft) deep. If soil weight is assumed to be 1450 kg/m3 (90 lbs/ft3), then 8 million tons of soil have been removed from the

Santa Cruz channel in the last 100 years. This amount represents only a small portion of the erosion that has occurred in southeastern Arizona (Renard, et. al., 1985).

In the Southwest, cyclic wet periods were followed by overstocking and the dry periods by livestock die-offs (Wagner, 1952). With each successive episode, perennial grass productivity decreased and shrub densities increased (Hastings and Turner, 1965). Rangeland cattle populations have decreased 87% in 90 years. Variations in annual precipitation are greater in southeastern Arizona than at any other location in the contiguous USA (Hershfield, 1962). There is also wide aerial variability in the same year (Renard and Brakensiek, 1976).

Historians have assumed that livestock were equally dispersed over the entire area. However, before 1930, livestock grazing and irrigated agriculture were more likely confined to lowland areas where reliable surface water supplies were available. If this assumption is correct, grazing and irrigated agriculture were limited to about 20% of the land area, or an estimated 1.5 million ha (3.7 million ac).

Early Range Research Work (1890-1930)

After documenting range deterioration, the Division of Agrostology (USDA) and the State Experiment Stations at Las Cruces, NM, and Tucson, AZ, began cooperative research in the 1890's to determine the feasibility of planting forage species to restore land productivity. Early reseeding efforts often failed because most of the species planted were not adapted to the arid Southwest. Adapted species often were planted in poorly prepared seedbeds and subjected to heavy grazing during establishment (Cox et. al., 1982). Even so, the early researchers were keen observers and collectively identified many problems of managing southwestern rangelands.

Organized Research (1930-945)

In the 1930's a major drought affected production and a depression destabilized the economy. Congress enacted the National Industrial Recovery Act (NIRA), and created the Work Progress Administration (WPA) and Civilian Conservation Corps (CCC). These provided for upland water development and fencing to separate grazing units (Cox et al., 1982; Johnsen and Elson, 1979). Livestock, previously concentrated in lowlands, were redistributed over new grazing lands covering the remaining land area.
However, funds made available to conduct range research were diverted to the military as the country entered the 1938 to 1945 World War II era.

Post World War II Era (1946 to Date)

Rangeland research was greatly expanded following World War II, resulting in the development of effective range management methods and the recovery of many areas. However, many other areas continue to decline. Decreasing forage production and accelerated erosion continue on areas dominated by woody plants and weeds (Gile, 1999). Also, some introduced forage species suppressed native species (Bock and Bock, 1996). The focus on rangelands is now also on wildlife, water quality and yield, biodiversity, recreation, and aesthetics (Fuhlendorf, 1999).

Many factors have contributed to the decrease in rangeland productivity including: climate changes, decreased fire frequency, excessive grazing and wild hay harvesting, and seed dispersal by livestock (McClaran and Brady, 1994) But the greatest threat to southwestern rangelands may be the large number of people moving to the "sun belt" to work and to retire.

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WATERSHED STUDIES IN THE SEMIARID SOUTHWEST

In the 1930's, the quality of agricultural land in much of the U.S. was deteriorating at a rapid rate and soil erosion was becoming a national crisis. The Agricultural Appropriations Act of 1930 was the first allocation of funds for erosion control experiment stations. Two early-effort pioneers were H.H. Bennett, charged with soil erosion investigations for the Bureau of Chemistry and Soils, and C.E. Ramser, head of the Bureau of Agricultural Engineering. The Soil Erosion Service (SES), created in 1933 in the Dept. of Interior, was established to carry out provisions of the National Industrial Recovery Act relating to the prevention of soil erosion. Under this Act, 39 erosion control projects were established around the country; Southwest locations were the Navajo Project in Albuquerque, NM and the Gila River Project in Safford, AZ. SES was later transferred to the Dept. of Agriculture under Henry A. Wallace, Secretary of Agriculture, and H. H. Bennett. In April 1935, the (SCS) was established to consolidate programs in engineering, erosion, the nurseries of the Bureau of Plant Industry, and the

Emergency Conservation Work Camps of the Forest Service. Thus the concern for soil and water conservation, which has continued through the ensuing 60 plus years, was created.

The first concern for watershed research resulted from an Upstream Engineering Conference in Washington, DC in September 1936. The need for experimental data for "demonstrational projects" such as rainfall intensities and frequencies and amounts and rates of runoff was stressed and 20 watersheds were proposed throughout the US to collect this experimental data. Unfortunately, only $100,000 was funded for the work. In 1937, six watersheds were selected in the Gila Project to begin rainfall/ runoff studies. The watersheds near Safford, AZ, with drainage areas between 380 acres (154 ha) and 780 acres (316 ha), were chosen to represent the erosional problems in tributaries to the Gila river above the San Carlos Reservoir. Six watersheds were also selected in the Rio Grande district; three in the Rio Puerco drainage and three near Santa Fe, NM. Drainage areas of these sites were between 44 (18ha) and 770 acres (312ha). The three near Santa Fe were abandoned in 1948, and the three west of Albuquerque on the Rio Puerco and the ones near Safford were discontinued in 1975.

In late 1953, the research functions and staff of the Research Division of SCS were transferred to a new organization, the Agricultural Research Service (ARS), and in 1957 formal control of the Abuquerque and Safford watersheds was transferred to ARS personnel in Tucson, AZ, to what was to eventually become the Southwest Watershed Research Center.

In the early 1950's, SCS had problems implementing upstream conservation programs affecting downstream water yield because of prior appropriation water laws which existed in most western states. Thus the Research Division was asked to select experimental watersheds where the role of watershed treatments on downstream water yield could be studied. A team of four specialists representing the disciplines of soils, vegetation and engineering selected two areas, one typical of the blue grama grassland area of southern Colorado and northern New Mexico, and another typical of the black grama grassbrush areas of southern New Mexico and Arizona. Based on a series of ranking criteria developed by the survey team, the upper Alamogordo Creek Experimental Watershed near Santa Rosa, New Mexico and the Walnut Gulch Experimental Watershed near Tombstone, AZ were selected. These areas, 175 sq km (67.7 sq mi) and 150 sq km (57.7 sq mi) respectively, were partially instrumented with runoff-measuring stations and precipitation gages in the fall of 1954.

Unfortunately, the concrete runoff- measuring devices constructed in 1954 were inadequately designed. By the end of 1955, four of the five devices on Walnut Gulch had failed, and the station on Alamogordo Creek was severely damaged. The failures resulted from inadequate hydrologic and hydraulic information. Hydraulic model work was needed to develop a device to measure the flash floods in the broad sandy channels, which experienced high velocities and heavy debris loads. Design criteria tests were begun by ARS engineers at the Outdoor Hydraulic Laboratory in Stillwater, OK to develop a new measuring device. In 1958, the first prototype of this new supercritical measuring flume was installed on the Walnut Gulch Experimental Watershed and in the ensuing years, nine additional devices of this design were constructed to complete the instrumentation network. On Alamogordo Creek, one additional measuring device was constructed on a large tributary before the project location was terminated in 1977. The original precipitation networks of a few recording raingages were expanded from the 1954 sparse networks until at one time there were 100 recording gages on Walnut Gulch and 67 recording gages on Alamogordo Creek.

On the Walnut Gulch Watershed, the work was greatly accelerated when the Southwest Watershed Research Center was funded as one of the recommended features of Senate

Document 59 in Fiscal Year 1961. At that time, a multidisciplinary staff was developed and objectives expanded to a broader-based range resource assessment. The passage of the Clean Water Acts of the 1970's led to major program changes to incorporate water quality problems in the research. Other changes such as the USDA's RCA of 1977 have affected the research program.

In 1970, cooperative research on three small watersheds on the Ft. Stanton Experimental Range was begun with New Mexico State University to evaluate grazing practices. The records and instrumentation were transferred to NMSU Range Science Dept. personnel in 1983.

In 1975, a cooperative project was started with the Forest Service Rocky Mountain Range Experiment Station and the USDA, Agricultural Research Service to deal with brush control on eight watersheds (drainage areas less than 4 hectares (10 ac)) in four different pasture systems in the Santa Rita Experimental Range near Tucson. In each instance, one of the two watershed pairs in each pasture was treated to kill the mesquite which dominate the vegetation while the other watershed was left as a check. This work continues today, with water quality sampling as an integral part of the work.

The Aridland Ecosystems Improvement Unit was merged with the Watershed Hydrology and Watershed Erosion Units in 1985 and the new unit became known as the Southwest Watershed Research Center. The current group has staff expertise in most aspects of rangeland resources with the possible exception of the grazing animal input which is being handled cooperatively with University of Arizona. The ecosystem improvement work was transferred to other ARS locations in 1990. New programs in the Research Center involving Decision Support Systems and Water Quality were started in 1991, and Global Change Research was added in 1992.

CLIMATE AND VEGETATION OF THE WALNUT GULCH EXPERIMENTAL WATERSHED

The Southwest Watershed Research Center field station is located at Tombstone, AZ. This area is characterized by mild temperatures, limited rainfall, and high evaporation rates (low relative humidity). The average frost-free season in Tombstone, at an altitude of 1,400 m (4260 ft), is 237 days, and has ranged from 205 to 277 days in the past 17 years. For January, the coldest month, the mean temperature is 8.4C (47F), and the mean minimum is 1.2C (34F). For July, the mean daily temperature is 26C (79F), with a mean maximum daily temperature of 34C (93F). The mean maximum temperature for June is the highest, 34.5C (94F), but the monthly mean is lower than for July, reflecting the lower nighttime temperatures. The temperature extremes recorded for Tombstone are -14C (7F) and 43C (109F). Evaporation and transpiration rates can be high during these hot summer months. From July through September, moist, unstable air masses generally advance into Arizona from the Gulf of Mexico or the Pacific Ocean and help produce a greater cloud cover. These air masses almost always produce moderate to intense thunderstorms, which develop most readily during the afternoon over the heated terrain. This moisture and the associated cloud cover cause an abrupt decrease in the pan evaporation for July through September.

Historically, the Walnut Gulch area was classified as Desert Plains Grassland. The xeric and most widespread grasses were black grama (Bouteloua eriopoda), found mainly on the uplands, and tobosa grass (Hilaria mutica) in the swales. The more mesic plant community was dominated by curley mesquite (Hilaria belangeri), black grama and other grama species on the upland and tobosa grass in the swales.

Today, much of the country, described by early settlers as grass covered, is predominantly brush. Nearly 60% of the Walnut Gulch watershed (the western, lower elevation half of the watershed) now supports desert shrubs, with varying amounts of the original grass species growing among them. The remainder of the area (the eastern mid-elevation half of the watershed) is grass covered, with a few scattered shrubs. Dominant shrubs on the watershed are Whitethorn (Acacia constricta var. vernicosa) is the most prevalent shrub; creosotebush (Larrea divaricata), tarbush (Flourensia cernua), and sandpaper bush (Mortonia scabrella). Dominant half shrubs include desert zinnia (Zinnia pumella) and burroweed (Happlopapus tenuisectus).

Changes in vegetation composition have been documented throughout the southwestern United States over the course of the last century. Data collected at Walnut Gulch provide an excellent opportunity to study these changes. During the summer of 1967, Dr. J. L. Gardner established, inventoried, and photographed 110 permanent vegetation transects at 55 raingages on the Walnut Gulch Experimental Watershed for the purpose of following any vegetation changes that may occur with time.

In 1994, Gardner's transects were relocated, inventoried and rephotographed. The following year, 28 new permanent vegetation sampling sites were established in the same manner as the original transects to provide adequate representation of all Natural Resource Conservation Service (NRCS) Ecological Sites on the watershed. In 1996, an annual vegetation sampling program was instituted for 14 of the sites. The 14 sites were selected to be representative of major shrub-dominated and grass-dominated subbasins for the purpose of providing vegetation information in support of hydrologic research. The measured data provide information on canopy intercept, plant height, diameter, and species composition, as well as ground cover and biomass (at two key sites) by plant lifeform. By comparing the 1967 data set with those collected in the 1990's, it was possible to evaluate long-term changes in these vegetation characteristics. It was also possible to follow inter-annual variability using the short-term database from the 1990's.

Preliminary analysis (Kidwell et al. 1998) indicates that overall canopy cover and species richness have increased across the Walnut Gulch Experimental Watershed over the last 30 years. Grass canopy cover on the grass-dominated sites showed significant increases, as did shrub canopy cover on both the grass and shrub-dominated sites. There were also significant increases in the absolute frequency (defined as the number of individual plants) of shrubs on grass-dominated sites, but no significant change in shrub species richness over the long-term. Half-shrubs were found to be clearly dominating the overall increase in both canopy cover and absolute frequency. No significant inter-annual variability was detected for grass or shrub canopy cover or species richness based on the short-term record. However, there was some inter-annual variability in the number of shrubs on shrub-dominated sites.

Further research is needed to better understand the processes behind these findings. Specifically, the inter-annual variability of precipitation as well as management practices must be evaluated, and rangeland health assessments should be performed to assess overall changes in ecosystem health and sustainability. Finally, continued intensive monitoring is critical to enable scientists to better understand the short and long-term trends in vegetation attributes as well as the driving forces behind them.

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PRECIPITATION NETWORKS FOR HYDROLOGIC RESEARCH

Personnel

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Almost all runoff from lower elevation rangelands in the Southwest occurs during the summer "monsoon" season, when intense rainfall exceeds the infiltration capacity. Moist air masses can push into southern Arizona, providing fuel for intense short-duration thunderstorms of limited areal extent. Primary sources of moisture are the Pacific Ocean and the Gulf of Mexico. Runoff from intense thunderstorm rainfall can cause severe flash flooding and soil erosion along with property damage and loss of life.

When the Walnut Gulch Experimental Watershed was established, very little was known about the areal distribution of thunderstorm rainfall. Starting in 1954 a recording raingage network was installed to quantify and characterize precipitation on the Walnut Gulch Watershed. Currently, 88 raingages are operating in and around the watershed to provide continuous precipitation data. Early precipitation research focused on summer events because about 70% of the annual rainfall and almost all runoff on Walnut Gulch occurs between mid- June and mid-September. Summer rainfall is the most dependable source of rangeland moisture, although individual events usually occur on only a portion of the watershed. In most summers, the minimum point rainfall is less than 50% of the maximum point rainfall, illustrating the extreme spatial variability of seasonal rainfall, as well as individual events. Summer rainfall has varied from a watershed average of 74 mm (2.95 in) to 240 mm (9.45 in). Point summer rainfall has varied from 40 mm (1.6 in) to 336 mm (13.2 in).

Currently, research is conducted to quantify watershed-scale properties of precipitation. Historical precipitation data are analyzed using linear trend analysis, spectral density analysis and interstation correlation. Time series analyses are used to describe temporal properties of precipitation at individual raingages and the interstation correlation analyses are used to evaluate the spatial dependence structure of the precipitation data. In addition to its use in characterizing precipitation, data collected from the Walnut Gulch recording raingage network contributes to the development of a multiobjective database used to address range management problems.

REINSTRUMENTATION AT THE WALNUT GULCH EXPERIMENTAL WATERSHED ANALOG TO DIGITAL/TELEMETRY

Personnel

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Background

The USDA_ARS Walnut Gulch Experimental Watershed is presently one of the premier facilities for hydrologic and related multi-disciplinary semiarid research. It serves as the primary "outdoor laboratory" for the Southwest Watershed Research Center. Hydrologic and soil erosion/sedimentation data collected on Walnut Gulch support our research programs involving basic hydrology, soil erosion, global climate change, rangeland health, and decision support systems. However, the viability of this "outdoor laboratory" is decreasing because of impending obsolescence of existing instrumentation analog data recording. The hydrologic instruments being used at Walnut Gulch were developed during the period 1920 to 1940 to measure precipitation and runoff-water flow depth and recorded data on paper analog charts. This antiquated technology is labor intensive in terms of chart data collection and data reduction. As such, research efforts are hindered because chart processing (analog to digital conversion) is more than two years behind. In addition, the instruments are wearing out and replacement parts are very difficult to obtain. To remedy this situation the SWRC began a multi-year effort in 1996 to fully reinstrument the Walnut Gulch Experimental Watershed with electronic sensor measurement, data logging capability, and radio telemetry to allow remote data transmission and station reprogramming. This reinstrumentation will greatly enhance our research and cooperative capabilities as well as maintaining the viability of hydrologic data collection and longterm continuous record.

After testing numerous commercially available electronic precipitation gages we did not find one that met our specifications. A high resolution, self contained, simple gage was designed by our field technicians and has been laboratory and field tested under simulated and natural rainfall. The gage consists of a precision, temperature compensated load cell, which measures the weight of a platform-mounted container that collects water from a precipitation event. As water accumulates in the container, the voltage output from the load cell changes. The voltages are sent to a data logger that records date, time, and voltage. Through calibration data relating voltage to precipitation depth, the voltage is converted to precipitation depth. The gage can measure 10 inches (305mm), has a depth resolution of 0.01 inches (0.25mm) and a programmable minimum time interval---we currently output the one minute average of 60 1 second readings. A very unique feature of the gage is that all electronics, data logger, and radio/modem components are housed in a metal belowground cylinder, thus reducing vandalism, lightning interference, and temperature effects. The gage solves the problems of the currently used mechanical gages by:

1. increasing precision and accuracy of precipitation timing, amount, and intensity,
2. eliminating mechanical friction and thus mechanism sticking,
3. eliminating marking pens, analog charts, and analog to digital conversion,
4. reducing site visitations by field technical personnel, and
5. allowing real-time monitoring of the gage.

The conversion from analog to digital output of the runoff measuring instruments was done by attaching a precision linear potentiometer to the output gear shaft of the currently used water-level recorders. The voltage output from the potentiometer is collected by a data logger which is accessed by radio telemetry. 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.

The installation of the Walnut Gulch electronic hydrologic network was completed in December, 1998. This network consists of 88 precipitation gages, 29 runoff measuring sites (10 stock ponds, 10 large Walnut Gulch flumes, and 9 smaller flumes-- 8 of which have sediment samplers), 3 weather stations, 3 long term soil moisture monitoring trenches, and 2 CO2 flux sites. Data from all these locations are transmitted to the Tombstone field office's data computer, saved, and written to the Tucson SWRC Sunserver using 56K phoneline on a daily basis.

GEOLOGY OF THE WALNUT GULCH EXPERIMENTAL WATERSHED

Personnel

W. R. Osterkamp (U.S. Geological Survey), S. N. Miller (University of Arizona), Del Wallace (ARS retired) and Fred Libby (ARS deceased)

The Walnut Gulch Experimental Watershed is part of the Basin and Range physiographic province, an area that was complexly deformed by late-Paleozoic to early-Mesozoic orogenies. The resulting geologic landscape is one in which ranges and hills of various igneous intrusive, volcanic, and bedded rocks have yielded sand and gravel that flank and cover parts of the source rocks. This alluvial fill material is known to be over 370 m (1,200 ft) deep in places, and serves as a huge reservoir for ground water. The topographic expression is that of gently rolling hills incised by a youthful drainage system (Libby, 1970). The oldest fan deposits of sand and gravel are generally folded, faulted, and well cemented, indicating that they formed during the Basin and Range deformation.

The oldest rock unit of the watershed, an unnamed gneissic granite of pre-Cambrian age, is exposed along a thrust fault (Gilluly, 1956, p. 13) near the headwater areas in the Dragoon Mountains. Stratigraphically above the gneissic granite, but exposed only at a southwestern edge of the watershed, is the middle-Cambrian Bolsa Quartzite, a transgressive-sea, littoral sand and gravel deposit (Bryant, 1968). More resistant to erosion than other formations, the Bolsa Quartzite forms high ridges and part of the southern divide. Also exposed in a small part of the headwaters area is the Gleeson Quartz Monzonite, an easily weathered intrusive rock of assumed early-Mesozoic age (Gilluly, 1956).

A series of marine limestones, with interbedded shale, sandstone, and dolomite, was deposited intermittently from late-Cambrian through Permian time and are exposed mostly in the Tombstone Hills. In ascending order and age they are the Abrigo, Martin, and Escabrosa Limestones, and the Naco Group, comprised of the Horquilla Limestone, the Earp Formation, the Colina Limestone, and the Epitaph Dolomite. Unconformably overlying the Paleozoic carbonate rocks in the southwestern part of the watershed are interbedded conglomerate, sandstone, and mudstone of the early-Cretaceous Bisbee Group (Hayes and Drewes, 1968). Immediately west of exposures of the Bisbee Group, at the southwestern basin divide, are outcroppings of the early-Miocene age Uncle Sam Porphyry, a quartz latite that locally is intruded by the easily weathered, Miocene-age Schieffelin Granodiorite (Gilluly, 1956).

Volcanic rocks of the watershed mostly record events late in the Basin and Range orogenies. The rocks include a resistant rhyolite of possible mid-Tertiary age that cuts limestones in the southern part of the watershed, the S O volcanics, which are a thick series of Miocene tuffs and hornblende andesite flows exposed mostly along the southeastern margin, and an unnamed olivine basalt of probable late-Miocene to early-Plioicene age that is exposed beside Walnut Gulch about a kilometer northeast of Tombstone.

Fan deposits and alluvium of the watershed, the remaining products of bedrock erosion, are divided into four main units. The oldest, Eocene to Miocene in age and informally named the Emerald Gulch Conglomerate, is nearly limited to channel bottoms in the southern part of the watershed; beds of the conglomerate are generally massive, 1 to 2 meters in thickness, deformed, and well cemented by ground-water deposits of calcrete. Many beds of the conglomerate include large clasts of limestone and sandstone derived from older bedded rocks and smaller fragments of volcanic rocks and flint (Alonso, 1997). Overlying the Emerald Gulch Conglomerate are dissected, generally undeformed beds of the Pliocene to mid-Pleistocene Gleeson Road Conglomerate. Preserved surfaces of the conglomerate are underlain by a mature soil of possible Sangamon age (300,000 years). Beds of the Gleeson Road Conglomerate contain less than 10 percent carbonate by weight, and thus have a low resistance to mechanical erosion; clasts are mostly related to the nearest bedrock exposures.

The Jones Ranch Alluvium, a late-Quaternary transition between the Gleeson Road Conglomerate and Holocene alluvium, represents the oldest deposits of the current drainage system and thereby includes fan deposits, terrace insets, and cienega deposits. Beds of the channel, flood-plain, and terrace deposits of the Jones Ranch Alluvium are up to 3 meters thick and may be capped by an immature paleosol with little or no carbonate cement. Where the alluvium has been deposited against fault scarps, such as in the upper part of the watershed, the thickness may reach several tens of meters.

The youngest beds of the watershed are mostly late-Holocene flood-plain, bar, and channel deposits of sand and gravel. These alluvial deposits refill parts of the channel incisions that formed along many streams as a result of post-development gully and channel erosion. Most of these deposits are bars and terraces that stand up to 2 meters above modern stream channels. Where recent gully erosion has exposed dark, carbonate-rich paludsal beds, radiocarbon dating suggests a mid-Holocene age of about 5200 years.

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SOILS OF THE WALNUT GULCH EXPERIMENTAL WATERSHED

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Soils within the Walnut Gulch Experimental Watershed (Appendix B) reflect the underlying geologic parent material. Much of the watershed is covered by Quaternary alluvial derivatives from various igneous intrusive and volcanic rocks with a high concentration of rock and gravel near the surface; where the soil is formed from limestone, it is relatively calcareous (Gelderman, 1970). Soils on the watershed range in maturity from freshly deposited alluvial material with scant development (the Bodecker series, for example) to soil weathered from bedrock with argillic horizon development (the Woodcutter series). A detailed soil survey was completed for the watershed in 1991 (Breckenfeld et al., 1993); data contained in this report will refer to results from this survey, including the use of updated series names from previous published surveys. Dominant land use on these soils is rangeland grazing.

Surface textures are typically very gravelly sandy loams and loamy sands, which together comprise over 60% of the surface. Other major surface textures include very gravelly and gravelly sandy loams, both of which account for over 11% of the watershed area. The remainder of the watershed is comprised of lesser amounts of sandy loams (5%), gravelly clay loams (4%), very gravelly loamy sands (3%), very gravelly clay loams (3%), and sand (1%). This range in surface textures illustrates the well-drained nature of the soils of the watershed, which are, typically for a semi-arid region, relatively lacking in silts and clays.

Soils near the headwaters of the watershed lay on typically steep slopes and are typically well-drained and shallow gravelly sandy loams. Dominant soils in this region are the Budlamp-Woodcutter and Blacktail complexes, which range in elevation from 1500 to over 1800 m (4900 to 5900 ft), in the Dragoon Mountains on steep slopes where the average annual precipitation is between 400 and 500 mm. (15.75" and 20"). Tree cover on these soils is mostly populated with oaks, while the understory is primarily grasses. These soils were formed from residuum parent material, chiefly slope alluvium and weathered granodiorite and contain abundant surface rock fragments.

The eastern portion of the watershed below the steep slopes of the Dragoons is typified by very gravelly sandy loams and is associated with grassland vegetation (sideoats grama, black grama, blue threeawn). The grassland portion of the watershed is underlain primarily with the Tombstone, Stronghold-Bernardino, and Elgin-Stronghold complexes which range in elevation from 1350 to 1580 m (4400 to 5200 ft). Average annual precipitation within this section is between 305 and 380 mm (12" and 15") and average slopes are between 10 and 30 percent. The underlying parent material throughout the eastern section of the watershed is mixed calcareous fan alluvium, and the soils are typically deep with a moderate erosion hazard and high concentration of gravel and rock fragments.

A shift in soil type and commensurate vegetation community between the eastern and western portions of the watershed occurs near the approximate center of the watershed. Loamy sands associated with shrub-steppe vegetation dominate the western section of the watershed. The dominant soil complex across much of the western portion of the watershed is the Luckyhills-McNeal complex, which formed from mixed calcareous alluvium. These deep soils have slight clay content and are well drained carbonate rich rocks with limited erosion hazard. Stream channels are typically incised, although some scattered bedrock control reduces the potential for downcutting and thereby exerts a widening influence.

Characteristics of soil derived from volcanic rocks, such as the S O Volcanic group and unnamed basalt, reflect the parent material. Minerals within the volcanic rocks weather to clays, and associated soils are typically gravelly and cobbly clay loams, such as the Graham-Lampshire and Graham complexes. These soils range in elevation between 1350 and 1700 m

(4400 and 5600 ft), and are generally shallow and well-drained with a high shrink-swell capacity due to the presence of clays. These soils tend to have a high rock content with significant surface rock fragments. Associated vegetation includes curly mesquite, threeawn, grama grass, and snakeweed.

Alluvium from limestone outcrops along the southern boundary of the watershed has produced soils characterized by a high calcium carbonate content. These soils, including the Mabray and Chiricahua series, tend to be located on relatively steep and rough slopes in association with barren rock outcrops. The surface has abundant rock fragments, which are also abundant in the rest of the profile. Shallow to very shallow in depth, these soils also typically have a shallow potential rooting depth. Grasses are prevalent, with some shrub invasion on the lower reaches of the soil communities.

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