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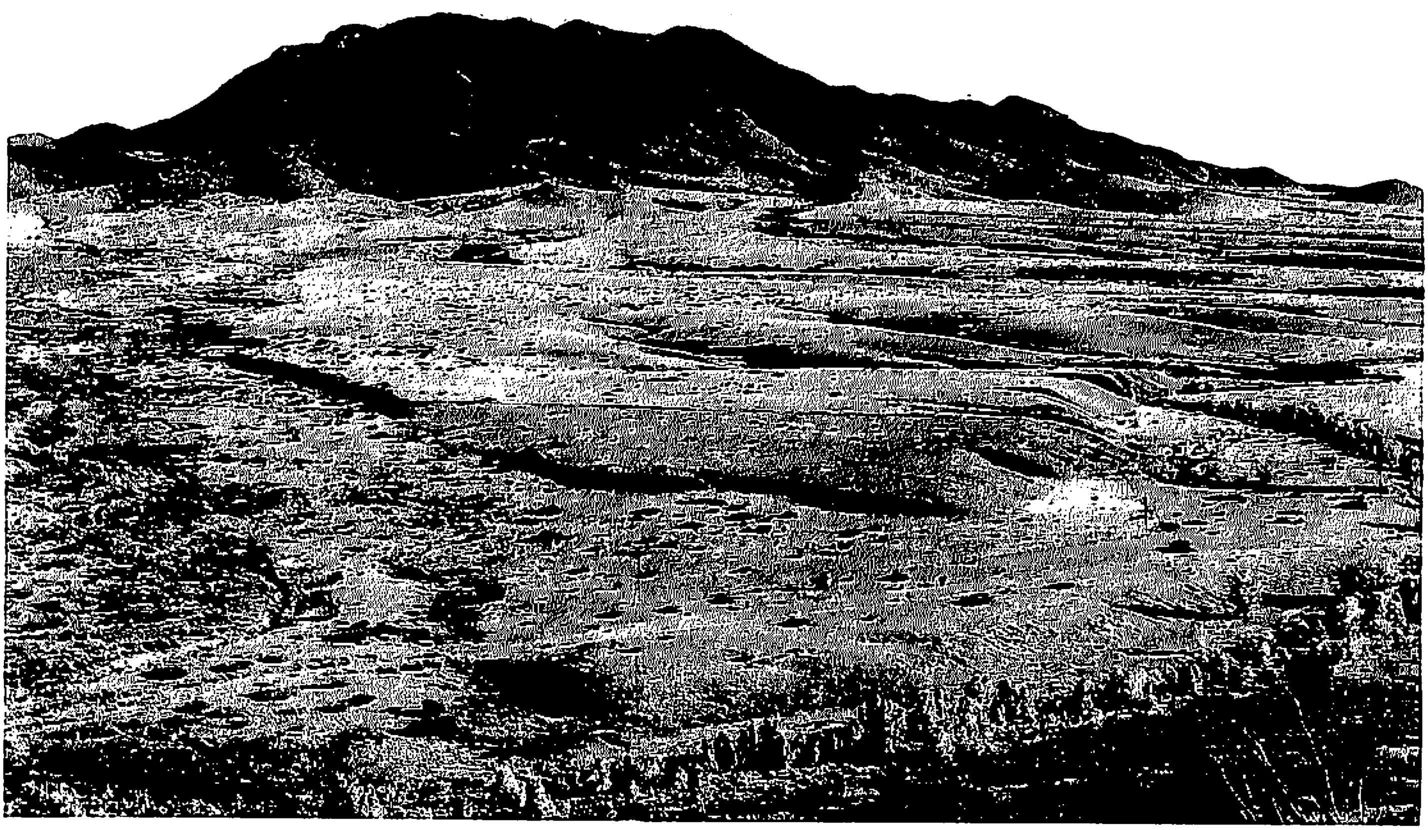
Runoff and Sediment Yield from Proxy Records:

Upper Animas Creek Basin, New Mexico

W.R. Osterkamp



Abstract

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Analyses of water- and sediment-yield records from the Walnut Gulch Experimental Watershed, the San Simon Wash Basin, and the Jornada Experimental Range, combined with observations of regional variations in climate, geology and soils, vegetation, topography, fire frequency, and land-use history, allow estimates of present conditions of water and sediment discharges in the upper Animas Creek Basin, New Mexico. Further, the records are used to anticipate fluxes of water and sediment should watershed conditions change. Results, intended principally for hydrologists, geomorphologists, and resource managers, suggest that discharges of water and sediment in the upper Animas Creek Basin approximate those of historic, undisturbed conditions, and that erosion rates may be generally lower than those of comparison watersheds. If conversion of grassland to shrubland occurs, sediment yields, due to accelerated upland gully erosion, may increase by 1 to 3 orders of magnitude. However, much of the released sediment would likely be deposited along Animas Creek, never leaving the upper Animas Creek Basin.

Keywords: runoff, sediment yield, erosion, Animas Creek

Author

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Cover photo: *View eastward to Animas Peak, southwestern New Mexico, with Animas Creek flowing from right to left in the midground (photo by R.M. Turner, USGS)*

Runoff and Sediment Yield From Proxy Records: Upper Animas Creek Basin, New Mexico

W. R. Osterkamp

Contents

Introduction

Effective rangeland management in the upper Animas Creek Basin of southwestern New Mexico depends on knowledge of basin characteristics including runoff and sediment-discharge rates. Data describing these rates are unavailable for the Animas Creek Valley and therefore, records from other watersheds are used as proxies. Conditions of climate, soils, vegetation, and topography in the Walnut Gulch/San Pedro River Basin, the San Simon Wash Basin, and at the Jornada Experimental Range are generally comparable to those of the Animas Creek Basin. Records of runoff and streamflow and of sediment yield from these areas permit comparison of hydrologic and sediment-discharge conditions with those in the upper Animas Creek Basin.

Cooperative studies in the upper Animas Creek Basin began in 1994 by the U.S. Geological Survey (USGS), the U.S. Department of Agriculture, Agricultural Research Service (USDA - ARS), and the USDA Forest Service, Rocky Mountain Research Station. Much of the upper Animas Creek Basin is occupied by the Gray Ranch. The purposes of the investigation were to characterize the land, water, and biotic resources of the area, and to anticipate effects on these resources due to fire, changes in land-use practices, or climate change. The characterizations are based on proxy data sets, published and unpublished, and a wide range of descriptive and interpretive reports. A principal research objective was to reduce, tabulate, compile, evaluate, and publish archived hydrologic, sediment-yield, climatic, vegetation, and land-use data from the Walnut Gulch Experimental Watershed and other research areas of the Southwest that were suitable for comparison and correlation with other data sets.

Part of the research objective is addressed by maps of the Walnut Gulch Experimental Watershed, generated by personnel of ARS, Tucson, AZ, which summarize conditions of geology, soils, and vegetation. Because sediment-discharge data, in metric tons per year (t/yr), expressed as sediment yield, in metric tons per square kilometer per year ($t/km^2/yr$), are dependent on runoff, streamflow totals are included. Many of the maps and water- and sediment-yield data on which interpretations of this report are based have not been published previously, and appreciation is extended to personnel of the ARS for making these data available for compilation.

Background and Literature Review

Rangelands of the present Southwestern United States have been used for grazing since 1540, when the Spanish explorer Francisco Vasquez de Coronado introduced cattle, sheep, and horses. Within 2 centuries, the activities of Spanish missionaries may have increased the numbers of grazing animals to the tens of thousands and, during the following century, the Mexican government encouraged further grazing on rangelands of present Arizona and New Mexico by granting land to people willing to establish ranches (National Research Council 1994, Sheridan 1995). Before displacement by Anglo-Americans, Mexican cattle in southern Arizona may have numbered up to 30,000, but the herds were probably restricted to areas of naturally occurring perennial water, leaving other rangelands unstressed (Sheridan 1995). Following the acquisition of much of these lands by the United States in 1853 (Gadsden Purchase) and after the introduction of railroads into the Southwest in the 1880s (Sheridan 1995), the influx of people and grazing animals accelerated. By about 1920, the adverse effects on rangelands in the Southwest and elsewhere were pronounced.

Passage of the Taylor Grazing Act of 1934 was recognition of the need for improved management of western rangelands. Since 1934, rangeland practices aimed at reducing undesirable effects of over-grazing have become increasingly more sophisticated. During the last half century, a national policy of fire suppression, regardless of the cause of the fire, may have resulted in unexpected vegetation change and erosion processes, particularly on Southwestern rangelands of semiarid climate and fragile plant cover. One result of development of better management practices by regulatory agencies was field-based research into the effects of grazing and other alterations of soils and vegetative cover.

Late Holocene geomorphic processes of the Southwest, including accelerated erosion starting about 1880, have been described in numerous publications. Two particularly detailed papers discuss gullying relative to environment change (Cooke and Reeves 1976) and processes of discontinuous ephemeral-stream channels (Bull 1997).

Studies of range-conservation practices on public lands (particularly those of the 12 western states administered by the Bureau of Land Management) began in 1941 and gained in intensity through the 1950s and 1960s (Peterson and Melin 1979). In 1953, the USGS began researching the effects of grazing practices on the hydrology and biology of drainage basins in arid and semiarid lands, and sediment discharge from those basins. A major part of this research was comparative studies of runoff and sediment discharge from grazed and ungrazed watersheds of western Colorado (Lusby 1978, Lusby et al. 1963, 1971). Results from grazed versus ungrazed watersheds during a 13-y period showed about a 40% average increase in runoff due to soil compaction by livestock, and a 50% average increase in sediment yield due to reduced vegetative cover. Related research includes studies on the hydrologic and sediment-discharge effects of sediment-detention dams and irrigation diversions in southeastern Arizona (Peterson et al. 1960), and of land-treatment practices in the Rio Puerco Basin of New Mexico (Burkham 1966). Of special relevance to rangeland management in the Southwest is the finding that excessive grazing typically is accompanied by conversion of grassland to shrubland, and the finding that sediment yield may increase 10 fold or more due to the conversion and to soil disturbance from grazing (Branson 1975).

Studies of changes in soil compaction and infiltration capacities from varying intensities of grazing include research by Leithead (1959), Branson et al. (1962), and Rhoades et al. (1964). Data from these and other studies, which directly relate grazing intensity to infiltration rates (Branson et al. 1981), demonstrate a marked impact. Information suggesting when reduction in infiltration capacities occurs was unavailable. Such a study could be a goal of future research.

Recent research at the Walnut Gulch Experimental Watershed, Arizona, related characteristics of precipitation, soils, vegetation, and management decisions (including grazing practices) to hydrology, erosion, and sedimentation (Renard et al. 1993). The studies examined the effects of different grazing intensities on shrublands and grasslands. Various changes have occurred in the Walnut Gulch watershed since 1880, when large numbers of livestock first were introduced including a generally greater degree of conversion from grassland to shrubland relative to length of time and grazing intensity.

Increased runoff and sediment yield from recently burned grasslands have been recognized at least since 1949 (Rowe et al. 1949, 1954). Recent studies in various environments have shown that sediment yield following rangeland or forest fire may increase as much as 3 orders of magnitude (Robichaud, USDA Forest Service, personal commun. 1997). A review of short-term effects by fire on the infiltration rates of different soils and vegetation types was presented by Branson et al. (1981). Interactions among fire, hydrology, landforms, and sediment yield over short to intermediate time scales were described by Swanson (1981). Most investigations of erosional effects of fire, however, have been conducted in the last decade. An impetus for research was especially strong following major fires in southern California in 1985, in and around Yellowstone National Park in 1988, and in the Boise National Forest and adjacent grasslands in 1959, 1986, 1994, and 1996.

Processes of sediment movement, including mass movements, were investigated by Wells (1987) following prescribed burns at the San Dimas Experimental Forest, California, in late October 1984. Storms during the following

2 months resulted in a total of 14 debris flows in the 4 studied watersheds. Related research of debris-flow activity (Wells et al. 1987) and response of a boulder-bed channel (Campbell et al. 1987) was conducted following the 1985 Wheeler fire in California. Increased soil erosion of up to 3 orders of magnitude from burned versus unburned basins of the Colorado Front Range was described by Morris and Moses (1987). Debris flows triggered by fire before the 1988 summer rainy season in the Huachuca Mountains of southeastern Arizona were studied by Wohl and Pearthree (1991). Shahlaee et al. (1991), Robichaud and Waldrop (1994), and Robichaud et al. (1994) conducted plot studies of runoff and sediment discharge from forested sites in Georgia, northern South Carolina, and northern Idaho, respectively.

Publications directly related to the Animas Creek Basin include a soil-survey of Hidalgo County (Cox 1973), descriptions of the geology and water resources (Schwennesen 1918, Dane 1961, Deal et al. 1978, Bryan 1995), and an inventory of vegetation change during the last century (Humphrey 1987). In an unpublished manuscript, "Comparison of erosion slope profiles from two watersheds", Lane et al. (1996) characterized runoff and ground-cover conditions at 2 rangeland sites in the upper Animas Creek Valley. Krider (1997) described the late-Quaternary geomorphic evolution of the valley. Studies, with maps of geomorphic surfaces in the southern Animas Creek Valley by K.R. Vincent and P.R. Krider, are in press.

Research Needs and Field Experiments

Research in surface processes confronts the problem of relating cause and effect. It may be difficult, for example, to ascertain whether an increase in fluvial-sediment load is the result of changes in land-use practices, generally grazing intensity in the borderlands of New Mexico and Arizona, or climate variability, such as anthropogenic change or change in the frequency of convective storms and lightning-induced fires, or possibly due to natural cycles triggered when a geomorphic threshold is exceeded. At the Walnut Gulch Experimental Watershed, changes in surficial processes may result from several causes, none of which can be identified confidently on the basis of a short period of data collection that may not represent long-term conditions.

A traditional solution to the problem has been to collect ancillary data that significantly increase the time represented, thereby permitting recognition of changes and trends in surface processes. Commonly used techniques that have low resolution but provide information for extended time intervals include radiometric or isotopic tracers and dating methods, a variety of paleontological approaches, and comparison of landscapes using old photographs, dendrochronology, and determination of clay mineralogy. An alternative to techniques that provide high-resolution information for short-time intervals and seems best suited for research in the Animas Creek Basin is direct measurement of landscape characteristics. Thus, traditional solutions to relating cause and effect are acknowledged, but research methods that emphasize direct measurements and yield high-resolution information to detect change and trends in surficial processes in the Animas Creek Basin and adjacent borderlands seem preferable.

A principal criterion for the selection of specific techniques to monitor geomorphic and hydrologic change is whether a site or small area is prone to erosion, sedimentation, or general landscape stability. If a small watershed is stable, data collected during a period of a decade or less will indicate that stability, but varying trends in erosion or sedimentation due to long-term change, such as alteration of climate by atmospheric loading of greenhouse gases, may be unobserved. An extreme example of this difficulty in comparing rates of change relative to temporal scale occurs in parts of the upper Animas Creek Valley. Over centuries or more, some landforms in the valley are unstable because they were products of a cool, moist climate (e.g., Pleistocene time)

(Hawley 1993), but on a short time scale they may show stability owing to the vegetation cover. Preferred sites for monitoring, therefore, are those where evidence of erosion or sedimentation is available and where site or small-watershed observations can be extrapolated to larger areal scales or to longer time scales.

Most bottomlands, and principally flood plains, of undisturbed basins are potential sinks for sediment over decade to century time scales. In valleys of arid and semiarid rangelands, fluvial sediment and slopewash deposits can only accumulate on low parts of hillslopes or in the channel and bottomland environments. In this context, bottomland includes relict lakebeds. Thus, wherever significant bottomlands occur, storage of sediment and possibly sorbed nutrients also occurs. Generally, deposition is greatest where channel gradients and stream competence are low and sediment loads are high. Monitoring sites, therefore, selected to optimize results, are placed along trunk channels draining areas where denudation rates are high, regardless of whether the sediment loads are the result of natural processes or of disturbances by land use or fire.

A variety of site-specific methods is available for quantifying water and sediment discharge and the storage of sediment in channels, on bottomland surfaces, and on low parts of hillslopes. All of these measurements require direct and indirect field observations or sampling and are inexpensive relative to most other data costs. Water discharges in ephemeral-stream channels are determined directly by discharge measurements and indirectly by slope-area measurements and use of crest-stage gages. Similarly, sediment discharge is measured directly by sampling suspended and bedload sediment and by measuring sediment deposited in a reservoir, tank, or on a playa floor. Sediment discharge is measured indirectly by installing in-place or automatic sediment samplers. Rates of movement of bed sediment can be estimated by constructing sediment traps, or pits, within an alluvial stream channel. As part of a research program to detect grazing- and fire-related changes in sediment discharge, the potential for relatively short-term change in bed-material sizes may be as important as is the amount or volume of channel sediment held in storage.

Valley-side, or upland, erosion detectable over a period of years to decades is measured by several techniques. Hillslope processes typically are monitored using erosion stakes, mass-movement pins to detect soil creep, monumented painted-rock lines, gully- and cliff-recession markers, repeated measurements of hillslope profiles, and any other appropriate means to identify change of hillslope characteristics through time. Surveys, including photography as applied to the Animas Creek Valley in this report, that demonstrate vegetation change along or in established transects and quadrats where hillslope change occurs can be used to complement the geomorphic observations.

The combined effects of variable intensities and sequences of grazing and occurrences of fire on sediment discharge are not known for Southwestern rangelands. Although sediment information generally is unavailable from the Animas Creek Valley and surrounding areas, sediment-yield data that provide a means for estimating rates of sediment discharge from undisturbed hillslopes and channels of the Animas Creek Basin are available from the Walnut Gulch Experimental Watershed, the Safford Valley, the San Simon Wash Basin, and other study areas of southern Arizona and New Mexico. These data and sediment discharges based on erosion-prediction models can yield baseline estimates of erosion and sedimentation conditions in the Animas Creek Basin.

Data provided in this report are assumed reliable. Runoff and sediment-discharge data, however, that are tabulated for sites in the Walnut Gulch Basin, at Creighton Reservoir and H-X Reservoir of the San Simon Wash Basin (appendix 2), and at sites on the Jornada Experimental Range (table 1) have not been verified as accurate relative to ARS or USGS procedures. Data for East Turkey Creek at Paradise, AZ; Cave Creek near Paradise, AZ; San Simon Creek near San Simon, AZ; and San Simon River near Solomon, AZ (appendix 2), and at sites along the San Pedro River (table 1) are summarized from published reports of the U.S. Geological Survey.

Table 1—Summary of unit-runoff and sediment-yield data from flumes, ponds, and model simulations of the Walnut Gulch Experimental Watershed, gage records of the San Pedro River and San Simon Wash, and reservoir surveys in the San Simon Wash Basin. Entries for unit runoff are mean runoff values for the period of record divided by basin area. Sediment yield is the mean annual yield for the period of record.

Watershed	Years[a]	Area, km²	Unit runoff, m³/s/km²	Sediment yield, t/km²/yr
F[b]105	23(6)	0.00182	0.000862	69.6
F106	28(6)	0.00344	0.000737	47.3
F122	13	0.00971	0.000321	
F01	25(9)	0.0129	0.009660	40.9
F102/102.1	30(3)	0.0146	0.000735	44.2
F112	28	0.0186	0.009710	
F124	19	0.0218	0.000443	
F103	30(9)	0.0368	0.000626	331
F104	30(9)	0.0453	0.000539	114
F121	21	0.0542	0.000448	
F125	12	0.0591	0.000243	
F4	37	2.27	0.000301	
F11	30	8.23	0.000326	
F3	35	8.98	0.000125	
F7	27	13.5	0.000086	
F8	27	15.2	0.000230	
F10	26	16.6	0.000107	
F9	26	23.6	0.000204	
F15	28	23.9	0.000107	
F6	31(50,L&R[c])	95.1	0.000136	122
F2	34	114	0.000117	
F1	36(50,L&R[c])	149	0.000107	175
P[d]201B	11	0.441	0.000383	305
P201G	9	0.441	0.000383	81.0
P207	16	1.07	0.000333	67.0
P208	5	1.08	0.000333	81.0
P212	14	3.16	0.000270	67.0
P213	18	1.47	0.000316	61.0
P214	21	1.53	0.000402	229
P215	12	0.340	0.000399	428
P216	16	0.955	0.000339	321
P220		0.611	0.000364	
P223	16	0.437	0.000507	195
RUSLE[e]-1		0.00124		51.5
RUSLE-2		0.000218		121
RUSLE -3		0.000070		27.0
SAN PEDRO-P[f]	70	3157	0.000536	
SAN PEDRO-C[f]	83(12)	3200	0.000500	154
SAN PEDRO-B[f]	10(9)	6450	0.000140	243
SAN PEDRO-R[f]	47	7581	0.000163	
SAN PEDRO-W[f]	14(14)	11,474	0.000141	193
C1[g] - Jornada	4(4)	0.000004	0.000434	19.3
C2 - Jornada	4(4)	0.000004	0.000519	20.6
C3 - Jornada	4(4)	0.000004	0.000573	25.3
C4 - Jornada	4(4)	0.000004	0.000621	43.1
E TURKEY CR[h]	6	21.2	0.001510	
CAVE CR, PAR[i]	6	101.0	0.002499	
S SIMON, SSN[j]	13	2108.0	0.000073	
S SIMON, SOLN[k]	35(23)	5677	0.000055	160
CREIGHTON R[l]	3(3)	275	0.000261	278
H-X RES[m]	3(3)	106	0.002147	388

[a]number of years of streamflow records; followed in parentheses by number of years of sediment-discharge or pond-deposition records
[b]flume
[c]information source Lane and Renard (1972)
[d]pond (small reservoir)
[e]results obtained by use of the Revised Universal Soil Loss Equation
[f]U.S. Geological Survey streamflow and sediment-discharge records for the San Pedro River measured at the Palominas, Charleston, Benson, Redington, and Winkelman gage sites
[g]plot numbers assigned by Bolin and Ward (1987)
[h]East Turkey Creek at Paradise, AZ, San Simon Creek Basin
[i]Cave Creek near Paradise, AZ, San Simon Creek Basin
[j]San Simon Creek near San Simon, AZ
[k]San Simon Creek near Solomon, AZ
[l]Creighton Reservoir, San Simon Creek Basin (data from Peterson et al. 1960)
[m]H-X Reservoir, San Simon Creek Basin (data from Peterson et al. 1960)

Watershed Characteristics

Various features of physiography, topography, climate, vegetation, and soils of the Walnut Gulch Experimental Watershed and the upper Animas Creek Basin are similar to each other and to many other parts of the Basin and Range Province of southern Arizona and southwestern New Mexico (figure 1). Much of the area between Tucson, Arizona, and the Animas Creek Valley, New Mexico (figure 1), classed as semidesert grassland (Brown and Lowe 1980), is a transition zone between the Sonoran Desert to the west and the Chihuahuan Desert to the east (figure 2). Although the Walnut Gulch Experimental Watershed lies fully in this transition zone, much of the watershed has Chihuahuan Desert vegetation and represents the western-most extension of that desert (R.M. Turner, written commun. 1998). Precipitation in the Sonoran Desert of Arizona is dominated by summer, or monsoonal, thunderstorms, whereas a significant portion of precipitation in the Chihuahuan Desert of New Mexico and Texas occurs as cool-season frontal storms. Sites discussed here are mostly in the Mexican Highland Section of the Basin and Range Province (Hawley 1993), which is a physiographic division bisected by part of the western continental divide.

Figure 1—Map of Arizona and New Mexico showing locations of Walnut Gulch Experimental Watershed 1) Animas Creek 2) San Simon Wash 3) Jornada Experimental Range 4).

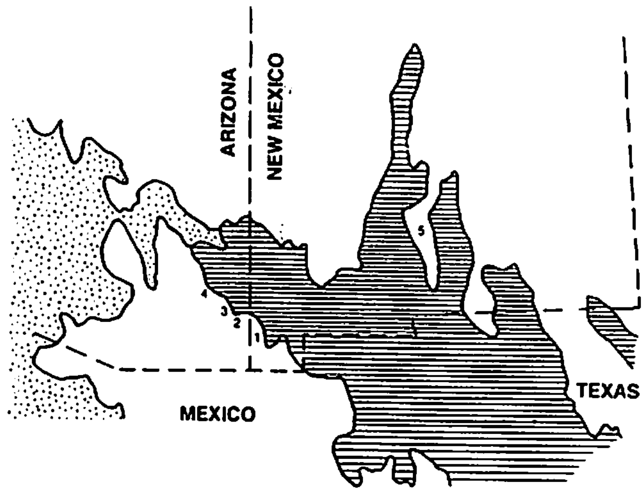

Figure 2—Distribution of Sonoran Desert vegetation (stippled) and Chihuahuan Desert vegetation (stripped), separated by uplands and semiarid grasslands (no pattern), in southern Arizona, southern New Mexico, west Texas, and parts of northern Mexico (generalized from Shreve 1951, Schmidt 1979, and Brown and Lowe 1980). Locations of the Peloncillo, Chiricahua, Dos Cabezas, Graham, and San Andres Mountains are indicated by the numbers 1, 2, 3, 4, and 5, respectively.

Walnut Gulch Experimental Watershed

The USDA-ARS Walnut Gulch Experimental Watershed, Tombstone, AZ, is the source of perhaps the most extensive data base for climate, hydrology, sediment discharge, soil characteristics, vegetation, and land-use practices ever collected in semiarid drainage basins of comparable size. The Walnut Gulch Basin, much of which is state and federal land, is representative of erosional conditions in large portions of the grazing lands of the Southwestern United States; research and data collection began in 1954 (figure 3).

The climate of the Walnut Gulch Basin, as indicated by weather records collected at Tombstone beginning in 1941, is gradational between semiarid and arid (Trewartha 1954). Weather-record summaries (table 2) show that

Figure 3—View of headcut and channel incision into fan deposits by a tributary to Walnut Gulch in the northeastern part of the basin; pronounced erosion of this sort has occurred locally during the last few decades (photograph by W. R. Osterkamp).

Table 2—Summary of weather data, from National Oceanic and Atmospheric Administration, U. S. Department of Commerce, for selected sites in southeastern Arizona and southwestern New Mexico.

Station Elevation[a]	Tombstone, AZ 1384	Wilcox, AZ 1277	Animas, NM 1347	Rodeo, NM 1253	Lordsburg, NM 1295	Douglas, AZ 1210	Hatch, NM 1234
Precipitation[b]							
January	21.1	22.1	18.5	18.5	23.6	16.3	12.7
February	20.8	22.9	13.5	15.0	17.5	15.0	9.4
March	15.5	18.5	11.9	14.0	17.8	12.2	6.1
April	7.4	6.6	5.1	2.8	6.6	6.1	5.1
May	5.1	5.6	4.3	3.0	6.6	4.1	8.9
June	13.0	10.7	11.2	8.1	11.7	12.7	13.7
July	93.5	59.9	57.9	66.3	50.0	84.1	51.8
August	88.9	64.5	60.7	54.9	53.3	75.2	56.1
September	38.9	29.0	37.8	34.8	33.8	31.8	37.3
October	16.3	16.5	26.7	25.9	26.9	18.3	27.2
November	16.0	18.5	14.0	10.2	14.0	15.2	10.4
December	22.1	23.9	25.9	25.1	26.2	21.1	18.8
Annual	358.6	298.7	287.5	278.6	288.0	312.1	257.5
Temperature[c]							
January	8.4	5.1	5.6	6.4	5.6	7.5	4.7
February	9.9	7.2	7.5	8.1	7.5	9.7	7.5
March	12.4	9.9	10.8	11.1	10.6	12.5	10.8
April	16.5	13.6	15.3	15.0	15.3	16.1	15.3
May	20.7	17.6	19.7	19.7	19.7	20.3	19.4
June	25.6	22.8	24.7	25.0	25.0	25.6	24.4
July	26.1	25.4	26.1	26.9	26.9	26.9	26.1
August	24.9	24.3	24.4	25.3	25.8	25.8	25.0
September	23.3	21.6	21.9	22.2	22.5	23.6	21.7
October	18.6	15.6	16.4	16.7	16.4	18.1	15.6
November	12.6	9.4	9.7	10.3	9.4	11.7	9.4
December	8.5	5.6	5.6	6.4	5.8	7.8	5.3
Annual	17.3	14.8	15.6	16.4	15.8	16.9	15.6

[a]values in meters
[b]values in millimeters
[c]average values in degrees celsius

Tombstone has hot summers and mild, relatively dry winters; about 60% of precipitation typically occurs in the monsoon season of July, August, and September. Annual precipitation is highly variable, from 170 mm in 1956 (Osborn 1983) to 437 mm in 1994 (based on records of 1956 through 1995).

Roughly 20% of the basin, principally in the Tombstone Hills of the southeastern part of the watershed, is directly underlain by an assortment of volcanic rocks. Quartz monzonite is in the Dragoon Mountains, and a granodiorite and a variety of carbonate and clastic beds are in the southwestern part of the watershed (Scott Miller, ARS, written commun. 1996; Alonso 1997) (figure 4). These rocks have been sources of a variable thickness of valley fill, cemented fan deposits and alluvium, of Tertiary and Quaternary ages that eroded from remnants of the Dragoon Mountains and the Tombstone Hills.

The older fan deposits, largely of Miocene age, typically are tilted and were deformed by faulting and folding before pedimentation (Melton 1965, Alonso 1997). The calcareous soils are generally well drained loams with abundant coarse sand and gravel near the surface (Gelderman 1970) (figure 5). At a grassland site presumed representative of much of the upper Walnut Gulch Basin, ground cover (i.e., rock cover or gravel lag), which develops through natural hillslope processes and minimizes the effects of rainsplash and rill erosion, averaged about 65% along one profile (Lane et al. 1995).

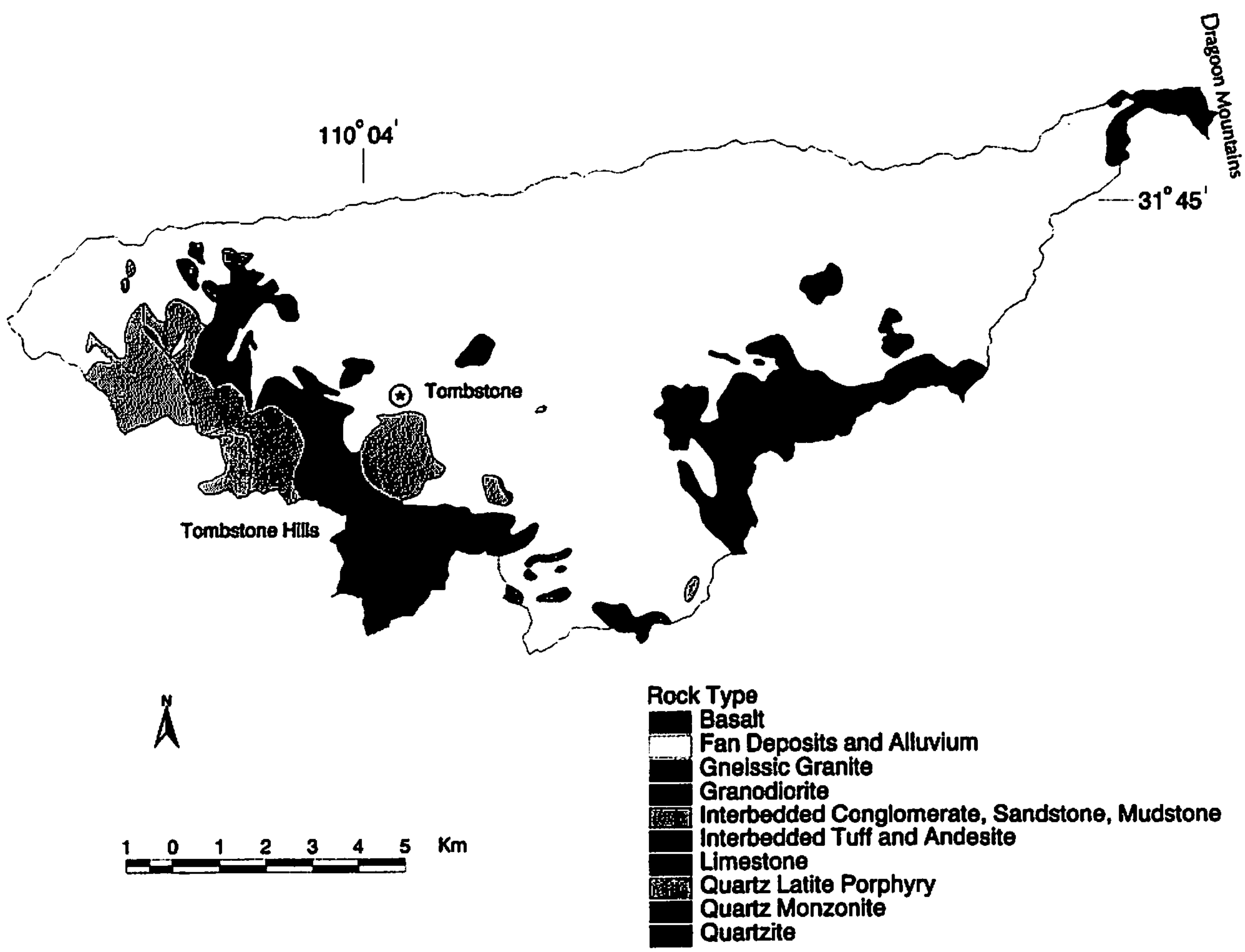

Figure 4—Rock-type distributions in the Walnut Gulch Experimental Watershed (unpublished map, courtesy of S. N. Miller, ARS).

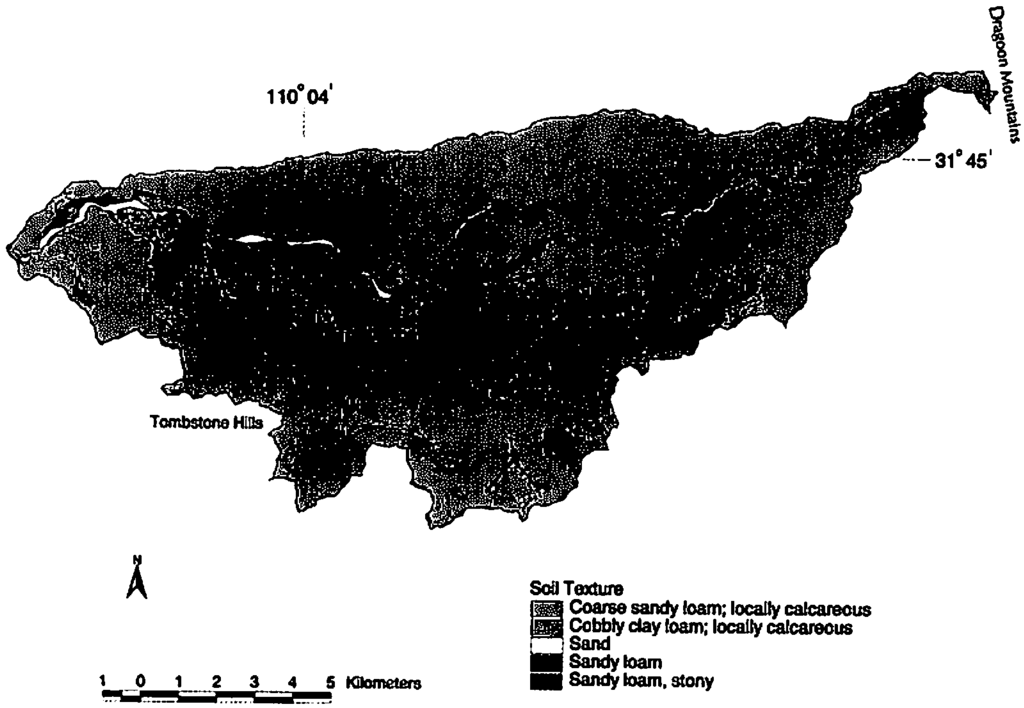

Figure 5—Distributions of soil texures in the Walnut Gulch Experimental Watershed (unpublished map, courtesy of S. N. Miller, ARS).

Subsequent surveys along 3 profiles in the same area of the Walnut Gulch watershed were conducted for this investigation and yielded ground covers ranging from 44% to 59%. In related research in the Walnut Gulch Basin, Simanton and Toy (1994) found a systematic increase in ground cover with hillslope inclination, regardless of vegetative cover or position in the watershed.

Fan deposits form widespread pediments of several ages in the San Pedro River Valley (Gilluly 1956, Melton 1965). Locally, they contain large percentages of limestone fragments from bedrock exposures in the basin, exhibit varying degrees of cementation (calcrete) from weathering of limestone clasts and reprecipitation as calcium carbonate, and are deeply incised by Walnut Gulch and its tributaries (Alonso 1997). In some upland tributaries of Walnut Gulch, headcuts and channel incision into the younger fan deposits (Quaternary age) remain active following an episode of intense gully erosion in the 1930s (figure 3).

Walnut Gulch typically has a wide, locally-braided ephemeral-stream channel that is tributary to the San Pedro River in southern Arizona (figure 1). Vegetation of about two-thirds of the experimental watershed, designated as the upper 149 km^2 of the Walnut Gulch drainage basin, is representative of mixed grass-brush rangelands of southeastern Arizona and southwestern New Mexico. Dominant increaser and invader species include creosotebush, white-thorn and catclaw acacias, tarbush, Lehmann lovegrass (Renard and others, 1993), and, locally, mortonia (figure 6). Snakeweed, burroweed, and cholla occur throughout the watershed where land use has stressed the cover of native grasses (for scientific names of plants mentioned in this report, see appendix 1). Photographic records show that about a century ago almost all of the basin was grassland dominated by black grama, curly mesquite grass, and tobosa grass (Hastings and Turner 1965) (table 3). Vegetation change may be related to the excessive

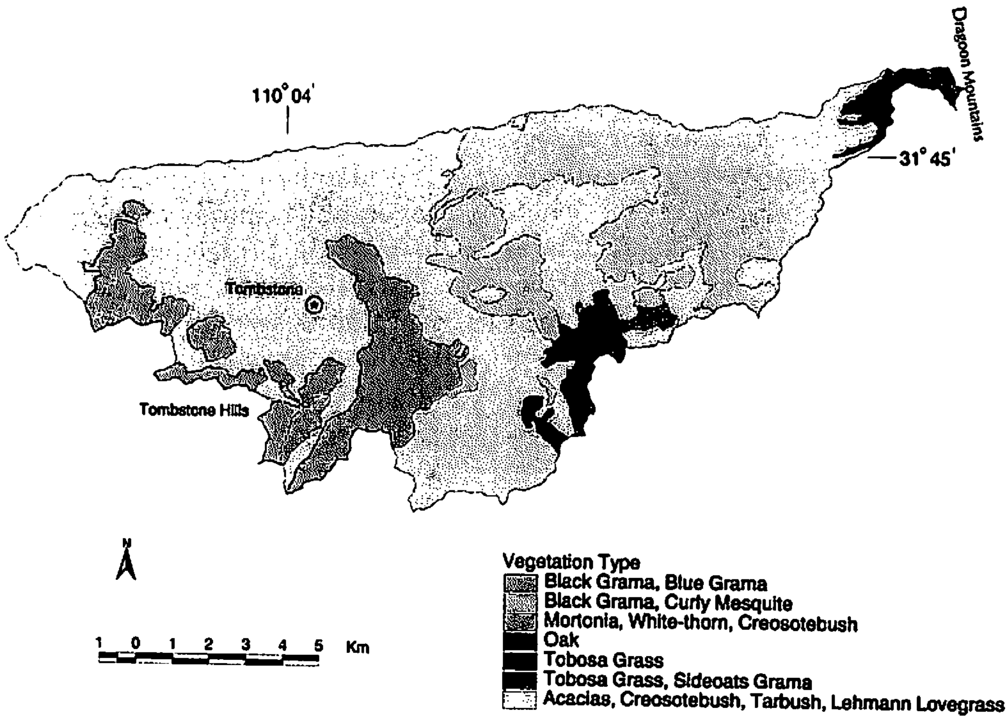

Figure 6—Distribution of dominant vegetation species, as vegetation types, in the Walnut Gulch Experimental Watershed (unpublished map, courtesy of S. N. Miller, ARS).

Table 3—Dominant plant species at selected sites of Arizona and New Mexico before intense grazing (predevelopment) and during recent years (post development).

	Walnut Gulch, AZ	Animas Creek Valley, NM	San Simon Valley, AZ and NM	Jornada Exp. Range, NM
Pre-development	black grama[f]	black grama[d]	blue grama[b]	black grama[a]
	blue grama[f]	blue grama[d]	hairy grama[b]	blue grama[a]
	curly mesquite[c]	tobosa[d]	sideoats grama[b]	tobosa[a]
	tobosa[c]	hairy grama[d]	mesquite[b]	mesquite[a]
	sacaton[c]	buffalo grass[d]	creosotebush[b]	creosotebush[a]
	mesquite[c]	beargrass[d]		
	agaves[c]	silverleaf oak[d]		
	beargrass[c]	pinyon pine[d]		
	sotol[c]	juniper[d]		
Post-development	creosotebush[f]	hairy grama[d]	hairy grama[b]	mesquite[a]
	white-thorn[f]	blue grama[d]	blue grama[b]	creosotebush[a]
	tarbush[f]	sideoats grama[d]	sideoats grama[b]	tarbush[a]
	snakeweed[f]	mesquite[e]	mesquite[b]	soaptree yucca[h]
	burroweed[f]	beargrass[d]	creosotebush[b]	black grama[h]
	Ln. lovegrass[f]	Mormon tea[e]	pinyon pine[g]	tobosa[h]
	acacia[c]	Emory oak[g]	Mormon tea[g]	burrograss[h]
	mesquite[c]	silverleaf oak[d]	yucca[g]	tarbush[h]
	chamiso[c]	mt. mahogany[d]		
	rabbitbrush[c]	golden-eye[d]		
	desert willow[c]	snakeweed[d]		
		Russian thistle[d]		
		pinyon pine[d]		
		juniper[d]		

[a]Buffington and Herbel (1965)
[b]Cox (1973)
[c]Hastings and Turner (1965)
[d]Humphrey (1987)
[e]Lane et al. (1996)
[f]Renard and others (1993)
[g]field observations
[h]Robert Gibbens, ARS, written commun., 1997

grazing that began in the Walnut Gulch Basin in the 1880s and continued through the first part of this century. Following reforms mandated by the Taylor Grazing Act in 1934, and establishment of rangeland research in the basin in 1954, policies of range conservation were generally applied.

Altitudes in the basin range from 1220 m at the lowest gaging station to 1843 m at a drainage divide in the Dragoon Mountains. Between the lowest gaging station and an upper-basin site at 1550 m, the Walnut Gulch channel gradient of 0.013 (m/m), steep relative to mean discharge, is typical of a braided-channel pattern. Nearly all streamflow in Walnut Gulch occurs between July and early October, and usually results from intense, convective thunderstorms or dissipating hurricanes. During a typical year, 5 to 10 flows pass most of the gaging stations. The channels of the drainage network are dry the remaining 99% of the time (Agricultural Research Service 1964).

The vegetation cover of grasses and shrubs and of certain individual species is correlated in varying degree with soil series and their physical and chemical characteristics. The distribution of one major species, mortonia, is limited to soils containing well developed calcrete (Agricultural Research Service 1964). The amount of plant cover is proportional to the distance from Tombstone, which is in the lower part of the basin. As the distance from Tombstone increases, grass cover increases, and shrub cover decreases. For example, vegetation in the vicinity of Tombstone is dominated by white-thorn and creosotebush, whereas at a site about 11 km east of Tombstone, sampled vegetation was predominantly short, warm-season grasses, and the canopy (vegetation) cover averaged about 40% (Lane et al. 1995). Along 3 other profiles in the same area, canopy cover averaged 64%. This correlation suggests that grass cover has diminished and shrub cover has increased since town settlement (about 1880) as a result of varying intensities of grazing during the early mining period in and adjacent to the town.

Predevelopment range fires were common in the Walnut Gulch Watershed, but fire suppression during the last century has probably contributed to the conversion of grassland to shrubland in much of the basin (L. J. Lane, ARS, oral commun. 1997). Where fire has occurred in recent decades, changes in runoff and sediment discharge have been difficult to identify. The stabilizing influence on soil by ground cover, but a canopy cover generally too sparse to provide protection from raindrop impact and rill erosion, may explain why sediment yield on desert rangeland does not appear to increase dramatically following fire (J. R. Simanton, ARS, oral commun. 1997).

Discharge records (table 1) from 22 flumes in the Walnut Gulch Basin vary in length from 13 to 37 y and records of inflow to 11 ponds are 5 to 21 y in length; areas represented by these data range from 0.00182 to 149 km^2. Listed also in table 1 are sediment-yield records for 8 of the flumes and deposition data for 10 of the ponds. Periods represented by these data vary from 3 to 21 y; the length of record has been extrapolated to 50 y at 2 of the flumes (Lane and Renard 1972).

The mean-runoff values that are provided in appendix 2 are given by water year (October 1 through September 30, ending in the listed year). To obtain a runoff volume in cubic meters for a flume or gaging station during a water year, multiply the mean runoff for the water year in cubic meters per second by 31,560,000, which is the approximate number of seconds in a year. Entries of unit runoff in cubic meters per second per square kilometers are listed to provide comparability among flumes or gage sites, and are values of mean runoff for a water year or the period of record divided by the drainage area. A column for sediment discharge (in metric tons/km^2) is provided for all sites and water years in appendix 2; no entry is provided if data were not collected or if equipment failure resulted in an incomplete record.

Runoff during a water year in the Walnut Gulch Experimental Watershed typically reflects specific times and months of precipitation (table 2). Calculations by Renard et al. (1993) for flume 103, using runoff data for water years 1965 through 1981 (appendix 2), suggest that about 37% of the mean annual runoff occurred during July, and that nearly

80% of the mean annual runoff occurred during the monsoon season July through September. The calculations also indicate that about 6.5% of precipitation is mean runoff whereas the remainder is lost through evapotranspiration (Renard et al. 1993).

Upper Animas Creek Valley

The upper Animas Creek Valley, including the 1300-km^2 Gray Ranch, occupies much of extreme southwestern New Mexico (figure 1); headwaters of the basin are in Sonora and Chihuahua, in northern Mexico (figure 7). The basin is bounded by the Guadalupe and Peloncillo Mountains on the west and the San Luis and Animas Mountains on the east and south; it empties northward toward Animas, NM (figure 7). Runoff and sediment-discharge data are generally unavailable for Animas Creek, but data were collected in the San Simon Wash Valley, west of the Peloncillo Mountains, and are presented in appendix 2 as proxies for conditions in the Animas Creek Basin.

Although the drainage basins of Animas Creek, Walnut Gulch, and San Simon Wash are similar in many respects, an important exception is surface-water hydrology. The Walnut Gulch and San Simon Wash Basins generally have well developed drainage networks, whereas runoff from the headwater areas of the Animas Creek Basin (partly in Mexico) collects in the Cloverdale Playas (figure 7). Animas Creek streamflow in the northern part of the basin enters an area of low slope, about 15 km north of the mouth of Indian Creek (figure 7), where the creek loses channel definition. Further north runoff continues to the Animas Playa (North and South Alkali Flats) west of Lordsburg, NM (figure 1). These ephemeral-lake basins, or playas, are topographic relics of late-Pleistocene time, when cooler, possibly wetter conditions caused higher runoff rates and sediment accumulations in bottomland areas than occur now (Hawley 1993).

Between elevations of 1420 m, north of Indian Creek, and 1570 m, downstream about 2 km from the northern limit of Cloverdale Playas (figure 7), the channel gradient of Animas Creek is about 0.004 (m/m). Relative to estimated characteristics of runoff, the gradient is suggestive of stable channel conditions.

Reflecting weather typical of the adjacent Chihuahuan Desert (Lordsburg and Hatch, NM, table 2), the Animas Creek Basin, as indicated by records from Animas and Rodeo, NM (table 2), has an arid to semiarid climate of hot summers and mild winters, with most precipitation occurring in the monsoon season (July through September) and lesser amounts as frontal-storm rain and snow in winter. Precipitation across southeastern Arizona and southwestern New Mexico generally decreases from west to east and tends to increase with elevation (table 2).

Most of the low-lying area of the Animas Creek Valley is underlain by fan deposits, alluvium, and lake deposits (Hawley 1993, Vincent and Krider 1998) largely from acidic volcanic rocks of the adjacent mountain ranges (Dane and Bachman 1961, Wrucke and Bromfield 1961, Cox 1973, Erb 1979, Hayes 1982). The surficial geology of upland areas of mountain blocks and pediment is dominated by bedrock and veneers of colluvium and talus of the volcanics. Soils that have formed on alluvium and related deposits are generally thick and fine textured, whereas soils of the uplands are thin, well-drained, gravelly loams (Cox 1973). Calcrete occurs in mature soils developed from limestone-bearing alluvium in the northeastern part of the upper Animas Creek Basin, but, owing to a deficiency of carbonate rocks elsewhere, is generally thinner and less widespread than in most parts of the Walnut Gulch Basin.

Continuous streamflow data are unavailable for Animas Creek. Annual maximum discharges, recorded at a USGS crest-stage gage, however, are available for the Animas Creek Station near Cloverdale, New Mexico (table 4), which is about 4 km downstream from the mouth of Clanton Draw (figure 7). The gage site (31- 34′ 15″ N; 108- 52′ 30″ W) is about 0.2 km west of New Mexico Highway 338. Peak discharges from the 76.4-km^2 contributing drainage basin for water years 1959 through 1994

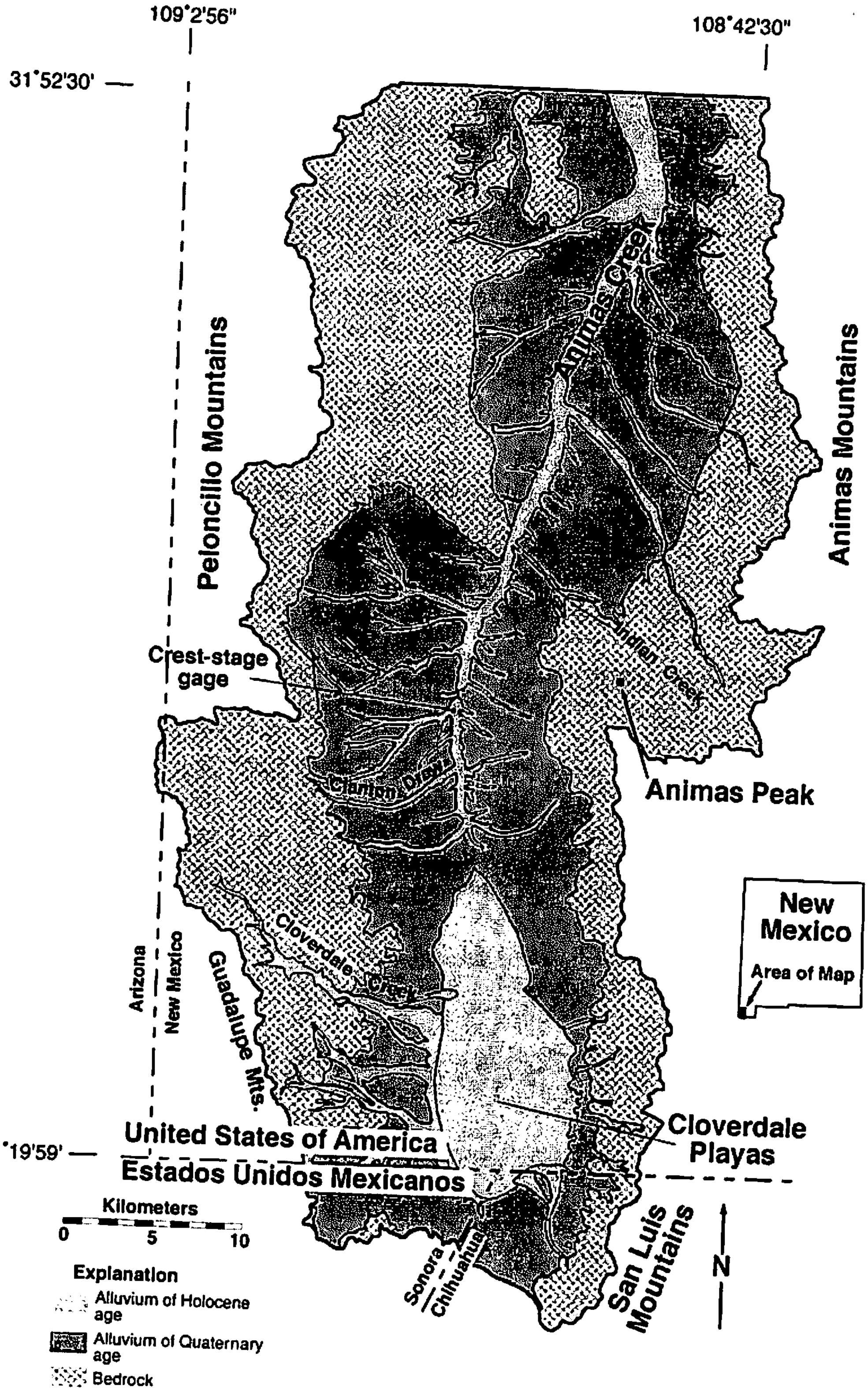

Figure 7—Map of upper Animas Creek Basin, New Mexico and northern Mexico (Sonora and Chihuahua), showing the general geology. Areas of intermediate shading are bedrock, areas of dark shading are Quaternary alluvium, and areas of light shading along streams are Holocene alluvium (modified from Vincent and Krider 1998).

Table 4—Annual maximum discharges (m^3/s), with gage heights (m above gage-datum elevation of 1530.1 m), for Animas Creek near Cloverdale, NM; water years 1959 through 1994.

Date	Gage Height, m	Discharge, m^3/s	Date	Gage Height, m	Discharge, m^3/s
0/0/59[a]	1.49	21	7/25/77	1.23	11
7/29/60	1.64	29	1/15/78	1.21	10
8/0/61[a]	1.70	33	8/15/79	2.14	71
0/0/62[a]	1.41	18	8/15/80	1.34	15
0/0/63[a]	1.78	39	8/11/81	1.35	15
9/12/64	1.96	55	8/19/82	0.88	2.8
9/9/65	1.27	12	9/26/83	1.73	35
8/8/66	1.09	7.1	10/2/83	1.34	15
7/14/67	1.35	15	9/16/85	1.40	17
8/2/68	1.52	22	10/16/85	1.69	32
7/17/69	1.55	24	12/16/86	1.11	7.6
9/5/70	1.06	6.4	9/1/88	0.73	1.0
7/24/71	1.86	45	7/25/89	1.25	12
7/24/72	1.76	37	3/10/90	1.52	22
7/15/73	1.34	14	3/2/91	1.55	24
7/16/74	1.47	20	12/5/92	1.28	12
10/13/74	2.37	96	9/3/94	0.99	6.2
9/7/76	1.32	14			

[a]day and or month unknown.

ranged from 1.0 to 96 m^3/s. Of the 32 water years for which dates of the annual maximum discharge are known, 24 occurred in the monsoon months of July (9), August (7), and September (8). The other 8 peaks occurred in January (1), March (2), October (3), and December (2). Because the Cloverdale Playas, about 18 km upstream from the gage site, pond much of the runoff from the uppermost part of the drainage basin, unit peak flows, in cubic meters per second per square kilometer, recorded at the Cloverdale gage site must be based on contributing, as opposed to total, drainage area to be directly comparable to unit peak flows from other watersheds.

Ranching by Michael Gray began in the upper Animas Creek Valley in 1880 as a cow-calf operation. Following incorporation into the Diamond A Ranch about 1890, the Gray Ranch and its headquarters became the southern unit of the Diamond A. Before the drought that began in the early 1890s that necessitated reductions in cattle herds, up to 75,000 cattle grazed on Diamond A land (Hilliard 1996). In recent decades, as many as 14,000, but generally about 8,000, cattle have grazed on rangelands of the Gray Ranch (Ben Brown, The Animas Foundation, written commun. 1998). Up to 23,000 head were present in the peak-grazing years 1915 through 1931. After 1931, herds were reduced to a range of 3,000 to 8,500 owing to obvious range deterioration and drought in the 1950s (U.S. Fish and Wildlife Service 1989). Since 1990, when the Nature Conservancy and later the Animas Foundation initiated concerted conservation practices, wildlife management has been a land-use objective (Peter Sundt, Consultant, written commun. 1993). Grazing and wildlife habitat remain the principal land uses of the Gray Ranch.

Lowland vegetation is mostly grasses, especially several species of grama, mesquite, Mormon tea, and invader species of golden-eye, Russian thistle, and snakeweed. Upland species include pinon, juniper, silverleaf oak, and mountain mahogany (table 3). Grazing during the last 100 or more years, and perhaps fire suppression during recent decades of erratic summer precipitation (Swetnam and Betancourt in press; J.L. Betancourt, USGS, personal commun. 1997), appear to have reduced grass dominance. Repeat photography at sites along the U.S.-Mexico border, however, indicates that the upper Animas Valley remains largely a grassland (Humphrey 1987) (figure 8). In comparison to bottomlands of the Animas Creek Valley, Medina (1986) recognized substantial change in riparian-zone vegetation of the Fort Bayard watershed, 150 km to the north-northeast, from about 1869 to the present. He attributed the vegetation change to severe impacts of grazing and deforestation and also identified upland gully erosion and changes in morphology of the largest channels draining the watershed (Medina 1986).

For more comprehensive descriptions of vegetation and other background information, refer to a detailed listing of plants identified and monitored on the Gray Ranch that was compiled by Peter Sundt for the Animas Foundation in 1993 in an unpublished manuscript, "Easement documentation report: the Gray Ranch, Hidalgo County, New Mexico. Other sources of detailed information on the biology and ecology of the upper Animas Creek Basin are an unpublished 1991 report by Esteban Muldavin, "Ecological values of Gray Ranch — vegetative communities in a landscape context," and an accompanying 1:100,000 vegetation map (1993) of the Gray Ranch developed from Landsat imagery by the New Mexico Natural Heritage Program and Technical Application Center, University of New Mexico, Albuquerque.

Rock-cover characteristics measured for this study along 3 profiles each at 2 north-facing sub-watersheds on fan deposits of the west slope of the Animas Mountains were similar to those of the Walnut Gulch Basin. One of the sub-watersheds (30- 31′ 15″ N, 108- 51′ 30″ W) was selected as representative of stable, ungullied conditions. The other sub-watershed (31- 36′ 16″ N, 108- 49′ 59″ W) discharges to a small channel with recent bed and bank erosion and incipient headcutting. For the 2 Animas Valley sites, ground cover showed averages of 57% and 61%, and canopy cover averaged 46% and 53% (figure 9).

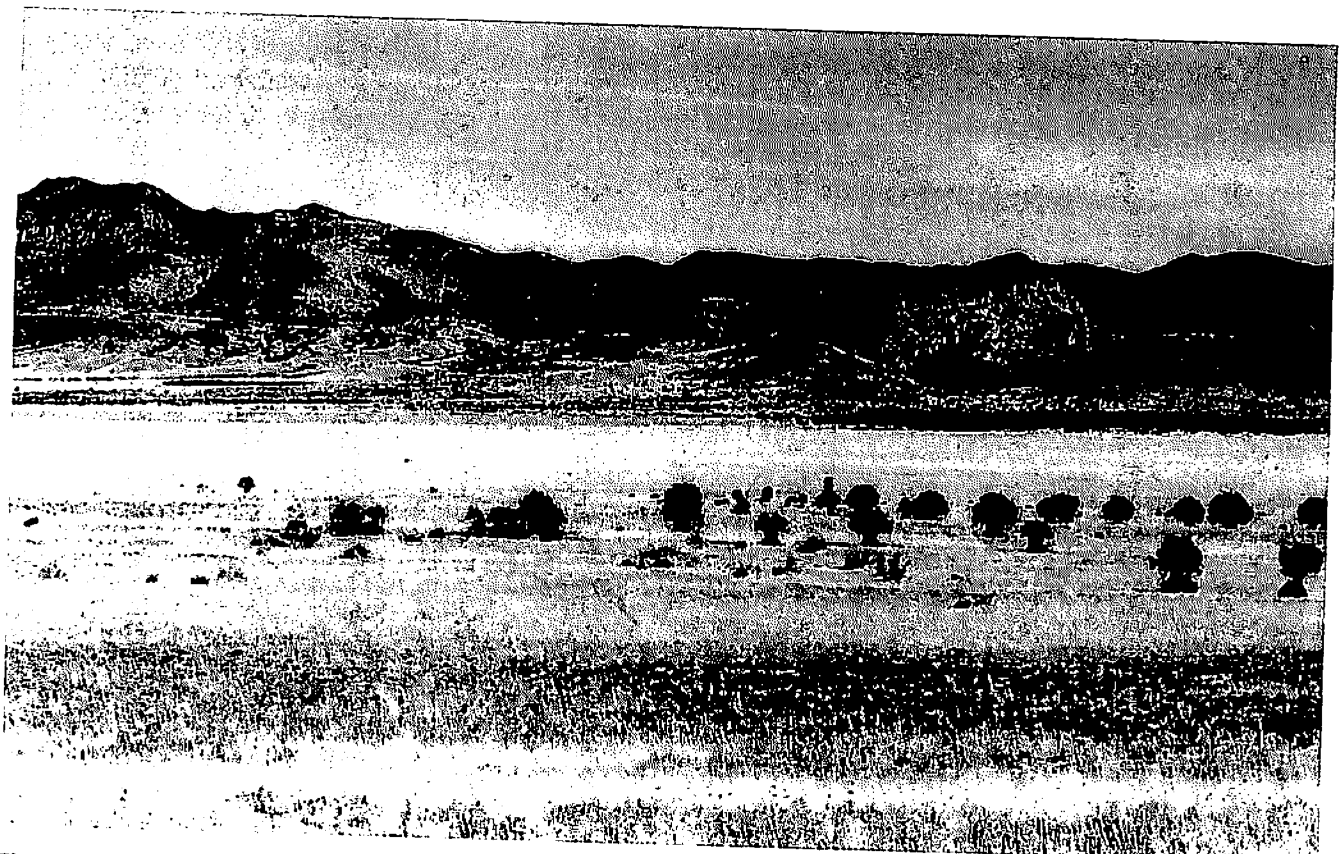

Figure 8—View to north-northeast toward Animas Mountains from near Cloverdale Playas, upper Animas Valley, showing grasslands and alligator junipers growing on playa beach sand (photograph by K. R. Vincent, 1996).

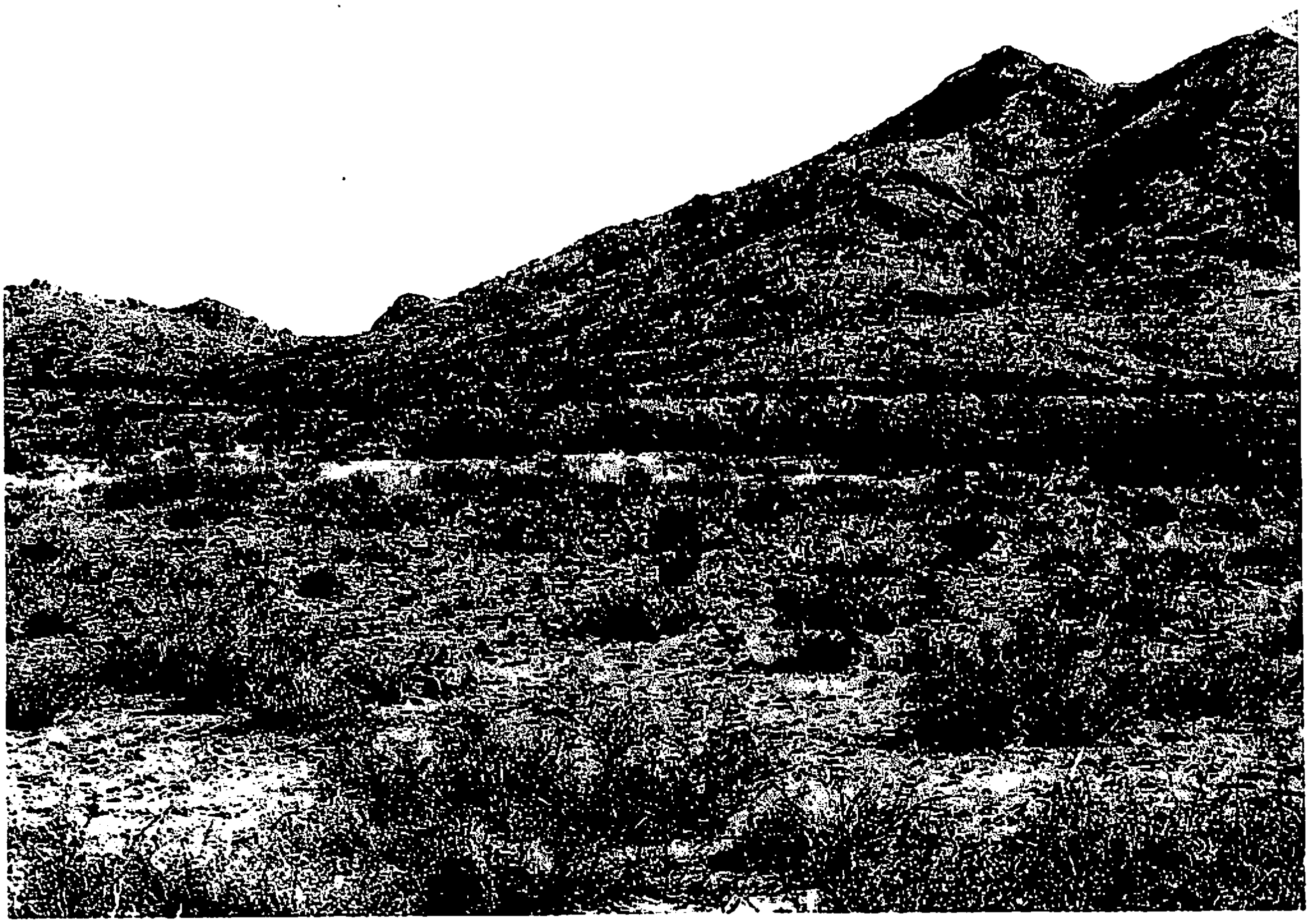

Figure 9—View to northeast of the alluvial surface west of the Animas Mountains near Animas Creek showing partial cover of shrubs, mostly mesquite, and rock fragments (photograph by K. R. Vincent, 1996).

Little is known about the magnitude and frequency of fires on rangelands of the Animas Creek Basin and in forested uplands bounding the basin. Regional analyses relating chronologies of fire scars and growth patterns of trees in the Southwestern United States, however, suggest a shift from predevelopment surface-fire frequencies of 2- to 10-y intervals in ponderosa pine forests to destructive crown fires during the recent period of fire suppression (Swetnam and Betancourt 1990). Analyses of pollen and charcoal recovered from cores collected at a site near Animas Creek (31-31′ N, 108-53′ W) and at 6 other cienegas of Arizona and Sonora, Mexico, indicate abrupt increases in stored organic material and decreases in charcoal following late 19th-century development. Before these changes, fire in the cienega areas may have occurred annually (Davis 1994).

Because shrubs, the spread of which is controlled by fire, were largely lacking on most desert grasslands of the Southwest before 1880, it is inferred that the occurrence of predevelopment range fires in the Animas Creek Basin and elsewhere averaged at least 1 per decade (McPherson 1997). Thus, fire suppression during the last 100 y may have contributed to the rapid conversion of grassland to shrubland in much of New Mexico and Arizona. Recognition of these changes has prompted the use of prescribed burns to kill shrubs and reduce the buildup of organic litter that may fuel crown fires. An example of a prescribed burn was the June 1997, Maverick fire, which charred more than half of a 4400-ha area in the southern Peloncillo Mountains, bordering the southwestern part of the Animas Creek Basin.

San Simon Wash Basin

The Peloncillo Mountains, along the Arizona-New Mexico border, separate the Animas Creek and San Simon Wash Basins. Flows in San Simon Wash head in the Peloncillo, Chiricahua, Dos Cabezas, and Graham Mountains (figure 2) and trend northwestward to Solomon, AZ (figure 1). Physiography, climate (as represented by weather summaries for Rodeo, NM) (table 2), native vegetation, and geology and soils (Cox 1973) of the upper San Simon Wash Basin are similar to those of the Animas Creek Basin. Unlike Animas Creek, however, the San Simon Wash is not interrupted by playas but flows through fine-grained valley fill to its confluence with the Gila River near Solomon, AZ (figure 1).

Owing to soil characteristics, and possibly to weather patterns, excessive grazing, and channel modifications, bottomlands of the San Simon Wash are among those of the Southwest that experienced pronounced gully erosion and related degradation (Peterson and Melin 1979). In about 1872, before settlement and the importation of large numbers of livestock, the valley of the San Simon Wash "was reportedly one of the outstanding grazing areas of the Southwest" (Peterson et al. 1960) (figure 10). By 1890, 50,000 or more cattle grazed in the San Simon Wash Basin, and depletion of grass was becoming severe (Tellman et al. 1997).

The severe overgrazing was compounded by erosive flooding of July 1890 (Hendrickson and Minckley 1984), followed by pronounced summer drought through 1892 (Bahre 1991). The drought continued into 1904, but historic floods in 1904 and 1905 again accelerated the erosion and gullying that had begun possibly 20 y earlier (Peterson et al. 1960). The gullying was exacerbated, if not initiated, by the flood of 1890 along a small diversion channel. The diversion had been excavated adjacent to the lower San Simon Wash about 1885 to convey flood flows into the Gila River (Hendrickson and Minckley 1984). Within 35 y, erosion had expanded the excavation to about 200 m in width and 10 m in depth (Tellman et al. 1997).

A short distance downstream, in Safford Valley, Arizona, major erosive floods of the Gila River in 1891, 1905, 1906, and 1916 had estimated peak discharges of 2800, 4200, 4000, and 3700 m^3/s, respectively (Burkham 1972). Headcuts and channel erosion initiated by these events continued through succeeding years and decades, accompanied by conversion of grasslands, largely of gramas, into shrublands dominated by mesquite and creosotebush (Cox 1973) (table 3, figure 10). As a result, the San Simon Wash Basin was one of several in which detailed rangeland studies were begun by the Soil Erosion Service in the 1930s and by the Soil Conservation Service in the 1940s and 1950s to mitigate rangeland deterioration (Peterson and Melin 1979).

Inspection of 30-min topographic maps generated from 1914 through 1917 suggests that in the lower part of the basin concentrated flow in tributaries and the main stem of the San Simon Wash did not extend upstream beyond the state border into New Mexico. Smaller-scale (15-min) maps of 1950 to 1958, however, show that by mid century an integrated channel or gully network extended into parts of the Peloncillo and Chiricahua Mountains. These maps indicate a channel gradient of 0.004 (m/m) in the San Simon Wash between a site at about 1020 m elevation that is 30 km downstream from the town of San Simon and a site at about 1310 m elevation that is 2 km west of the Arizona-New Mexico border. Relative to drainage area and runoff (table 1), this gradient is consistent with a well defined, non-braided channel.

Annual runoff data for the San Simon River near Solomon, AZ, 1936 through 1970, and sediment-yield data, 1936 through 1958, are listed in appendix 2. Runoff data only for short periods are provided for San Simon Creek near San Simon, AZ, Cave Creek near Paradise, AZ, and East Turkey Creek at Paradise, AZ. Inflows of water and sediment to 2 reservoirs in the San Simon Wash Basin, the Creighton and H-X Reservoirs, are listed for 1956, 1957, and 1958. In contrast to the Gila River in Safford Valley, where about 70% of its

Figure 10—View to the east of the bottomlands of the San Simon Wash, about 10 km south of San Simon, AZ. Nearly to the Peloncillo Mountains in the background, the vegetation is largely restricted to creosotebush (photograph by W. R. Osterkamp, 1997).

perennial streamflow results from winter frontal storms, most of the ephemeral streamflow in the San Simon Wash occurs in the summer months (Burkham 1972) following monsoonal precipitation.

Causes of the severe gully erosion in the San Simon Wash Basin of 50 to 100 y ago cannot be identified with confidence, but excessive grazing, exacerbated by erodible soils, fire suppression, and drought followed by flooding, was likely a significant influence. In addition, elevations of the San Simon Wash Basin are lower than those of the Walnut Gulch and upper Animas Creek Basins, and pre-development vegetation, including mesquite and creosotebush (Cox 1973), probably provided little resistance to the rill and gully erosion in the lowest areas of the watershed.

Jornada Experimental Range

Established in 1912, the Jornada Experimental Range, between Las Cruces and San Marcial, NM (figure 1), occupies part of the *Jornada del Muerto* (journey of death) so named by 16th- and 17th-century Spanish travelers due to the lack of water in the area. Rangeland research and publications describing the work by the USDA and the territory of New Mexico, however, date from 1908. Vegetation records for various years starting in 1858 are available in Buffington and Herbel (1965). In 1979, about 5.7 km^2 of the experimental range was designated as a Long Term Ecological Research (LTER) site (Havstad and Schlesinger 1996).

The Jornada Experimental Range, on the west flank of the San Andres Mountains (figure 2), comprises 783 km^2 of the northern Chihuahuan Desert (figures 1, 2) and has an arid climate typical of southern New Mexico (see weather summary for Hatch, NM, table 2). Precipitation records for the Jornada Experimental Range Headquarters begin in 1915. For the period through 1971, mean annual precipitation was 211 mm, 53% of which fell erratically in the monsoon season of July through September (Houghton 1972). Reflecting the geology and climate of the area, soils are mostly strongly calcareous silt and sand loams formed from fan deposits derived from Paleozoic rocks of the San Andres Mountains (Soil Conservation Service 1963).

Vegetation in much of the Jornada Experimental Range has changed significantly since the mid-19th century, presumably due to heavy grazing, related seed-dispersal processes, and drought (Buffington and Herbel 1965). In early August 1864, following weeks of unusually frequent showers, Sergeant George Hand of the Union's California Column, described the Jornada as a lush green meadow, with "grass as high as a man's head" (Carmony 1996). The conversion of grasslands, dominated by black grama, blue grama, and tobosa, to shrublands of creosotebush and mesquite (table 3) has been accompanied by an irreversible loss of silt and clay fractions from the surface (Schlesinger et al. 1990). The effects of the vegetation replacement and interrill erosion on runoff and sediment-discharge characteristics are unknown, although recent plot studies of erosion provide an indication of current conditions (Bolin and Ward 1987).

Despite the likely impact of heavy grazing, parts of the Jornada del Muerto continue to support excellent canopy covers of black grama, burrograss, and tobosa. Yet, where increasers, such as creosotebush and mesquite, have encroached on black-grama grasslands, the subsequent exclusion of grazing has not resulted in a reversal to a grass cover (Robert Gibbens, ARS, written commun. 1997). The area of the Jornada Experimental Range shown in figure 11 was dominated by black grama. Grazing has not been permitted to the right of the fence since 1935, but creosotebush continues to be dominant.

Figure 11—View of rangeland dominated by creosotebush, Jornada Experimental Range, New Mexico. Before excessive grazing, the area was dominated by black grama (photograph by Robert Gibbens, ARS, 1997).

Water and Sediment Discharges

Various techniques are available to identify the effects of land-use practices and natural landscape change. Measurement of vegetation change (especially over a decadal time scale), runoff characteristics, and soil-moisture conditions are examples that include the use of vegetation transects and repeat photography, streamflow-gaging structures and plot studies of runoff (from natural and artificially applied rainfall), and time-domain reflectometry (Zegelin et al. 1989). Erosion, as indicated by sediment discharge, is a process that generally varies dramatically in arid and semiarid environments with differing conditions of grazing intensity, fire occurrence, encroachment of exotic or invasive vegetation, or rainfall/runoff relations. Sediment-discharge data that would be useful as a baseline indicator of rangeland health at the Gray Ranch are unavailable. An extension of the stated purposes of this study, therefore, is to interpret baseline, or relatively natural, sediment-yield conditions for the Animas Creek Basin using summaries of data from comparable watersheds in the Walnut Gulch Basin and elsewhere.

Sediment yield and, to a lesser degree, runoff from undisturbed rangelands of the Southwest and elsewhere, vary also with drainage-basin area (Toy and Osterkamp 1995). Soil loss from upland surfaces and watersheds smaller than about 1 km^2 is a function principally of rainsplash-particle detachment, overland-flow transport of the particles, and rill and interrill erosion. Sediment yield from drainages larger than 1 km^2 is compounded by channel erosion, deposition of sediment in uplands of low slope and on surfaces of alluvial bottomlands, soil creep and other forms of mass movement, and disturbance due to fire, bioturbation, and physical processes including freeze-thaw sequences and wetting and drying episodes (Osterkamp and Toy 1996). Interpretations suggested by this analysis, therefore, are presented relative to the increase in drainage area in the downstream direction.

Appendix 2 contains runoff and sediment-discharge data from the Walnut Gulch Basin, the San Simon Wash Basin, and the Jornada Experimental Range. Summaries of these data are in table 1. Additional streamflow and sediment-discharge data that are available from hydrologic-data reports of the USGS for sites along the San Pedro River are not listed in appendix 2 but are summarized in table 1. Appendix 2 includes: 1) annual runoff data for 22 flume sites and 11 ponds in the Walnut Gulch Watershed and 4 gage sites and 2 reservoirs in the San Simon Wash Basin and 2) annual sediment-discharge or deposition data for 8 flume sites and 10 ponds in the Walnut Gulch Watershed and 1 gage site and 2 reservoirs in the San Simon Wash Basin.

Runoff

Unit runoff in cubic meters per second per square kilometer, varies through time and with watershed area but averages about 1×10^{-4} from Walnut Gulch, 6×10^{-5} from the San Simon Wash, and, based on very limited data, 5×10^{-4} from small upland plots in the Jornada Experimental Range (table 1). These rates of mean runoff compare to estimates of roughly 2×10^{-3} for the Walnut Gulch and San Simon Wash areas, and 1×10^{-3} for the Jornada area, which were generalized for the conterminous United States by Dunne and Leopold (1978). The runoff rates proposed by Dunne and Leopold (1978) may be poorly representative because they are based mostly on records from upland sites of perennial streamflow for water years 1921 through 1945.

Because upland soils in the Walnut Gulch (figure 5), Animas Creek, San Simon Wash, and Jornada areas are typically mapped as well-drained sand and gravel loams, it is anticipated that rainfall-runoff conditions for interfluves are generally similar for the Walnut Gulch, Animas Creek, San Simon Wash, and Jornada areas. The soil conditions are suggestive of high infiltration capacities and may contribute to the relatively low runoff rates. Owing to bedrock conditions and the geomorphic history, however, Animas Creek downstream from Clanton Draw to about Indian Creek (figure 7) generally has either perennial underflow or intermittent streamflow. Downstream from the Indian Creek confluence, Animas Creek enters a zone where faulting has lowered bedrock levels resulting in fully ephemeral streamflow (K. R. Vincent, National Research Council Associate, oral commun. 1997).

Runoff data in appendix 2 are given as annual means and, therefore, fail to show that most rangeland streamflow in southern Arizona and southwestern New Mexico is flashy, in direct response to summer convectional storms. Except along the Animas Creek main channel upstream from Indian Creek, episodic streamflow typically is reduced through transmission loss as water readily infiltrates into unsaturated alluvial deposits. As streamflow decreases in the down-channel direction, entrained sediment is deposited.

The flashiness of streams in southern Arizona and New Mexico is illustrated by annual flood-peak data, expressed as unit discharges, for Animas Creek near Cloverdale, New Mexico, and for flume 6, Walnut Gulch near Tombstone, AZ (table 5). The annual peak discharges for Animas Creek, water years 1959 through 1994 (table 4), are from hydrologic records of the USGS. The annual peak discharges for Walnut Gulch, water years 1963 through 1992, are from unpublished records of the USDA-ARS (John Masterson II, ARS, written commun. 1998). The range of flood peaks extends through 2 to 3 orders of magnitude. The flood of record for flume 6, Walnut Gulch, exceeded mean unit runoff (F6, table 1) by more than 4 orders of magnitude.

Listed also in table 5 are average recurrence intervals, or return periods, (T_r) in years, calculated from the annual flood-peak data. Figure 12 shows the unit-peak discharge and return period for Animas Creek (diamonds) and flume 6, Walnut Gulch (squares). Unit runoff during high-frequency events is similar in the 2 drainage basins, but during low-frequency floods in Walnut Gulch it is up to 1.6 times that of Animas Creek. The difference may be from the combined effects of: 1) greater monsoonal and mean-annual precipitation in the Walnut Gulch Watershed than in the Animas Creek Valley (table 2), 2) a generally better cover of native grasses in the Animas Creek Valley than in the Walnut Gulch Watershed (table 3), and 3) soils in the Walnut Gulch Watershed that are more calcareous and degraded (figure 5) and thus, more likely to yield runoff during precipitation events than are soils of the Animas Creek Valley. Because monsoonal storms generally are of small areal extent, the times of floods differ for the 2 areas. For example, the 2 largest discharges for Animas Creek (table 5) occurred in 1975 and 1979, whereas the 2 largest events at flume 6, Walnut Gulch, occurred in 1964 and 1967.

Runoff Relative to Drainage-basin Area

Figure 13 is a graph of the unit-runoff data listed in table 1 for Walnut Gulch and the San Pedro River. Unit runoff in cubic meters per second per square kilometer decrease linearly to a drainage-basin area of about 30 km^2. The gentle rate of decrease is possibly due to storage of a small but increasing portion of the ephemeral streamflow in channel deposits of Walnut Gulch and its larger tributaries as flows proceed downstream. As drainage-basin area approaches 100 km^2, the relative volume of alluvium available for storage of Walnut Gulch discharge by transmission loss increases, and the unit runoff declines at an increased rate. Streamflow in the San Pedro River downstream from its confluence with Walnut Gulch is intermittent to perennial and is augmented by seepage from saturated rocks and alluvium through which it flows. Rather than being reduced by transmission loss, the result is increasing unit runoff in the downstream direction.

In comparison, 6 mean values of unit runoff for the San Simon Wash Basin are plotted (+) in figure 13. Based in part on the shape of the curve for Walnut Gulch and the San Pedro River, a line of relation is interpreted for the data points. Unlike Walnut Gulch, the San Simon Wash receives perennial runoff from headwater areas that approach 3000 m elevation in the Chiricahua Mountains. Thus, unit runoff from areas smaller than 1000 km^2 is

Table 5—Annual peak discharges, relative to drainage area, and associated recurrence intervals for Animas Creek near Cloverdale, NM, and Flume 6, Walnut Gulch near Tombstone, AZ.

Animas Creek near Cloverdale, NM drainage area: 76.4 km^2 water years 1959 through 1994		Flume 6, Walnut Gulch near Tombstone, AZ drainage area: 95.1 km^2 water years 1963 through 1992	
Return period, T_r	Discharge, m^3/s/km^2	Return period, T_r	Discharge, m^3/s/km^2
36	1.26	32	1.96
18	0.93	16	1.38
12	0.72	10.70	1.12
9.00	0.59	8.00	1.07
7.20	0.51	6.40	0.68
6.00	0.48	5.33	0.68
5.14	0.46	4.57	0.63
4.50	0.43	4.00	0.60
4.00	0.42	3.56	0.57
3.60	0.38	3.20	0.56
3.27	0.31	2.91	0.44
3.00	0.31	2.67	0.43
2.77	0.29	2.46	0.39
2.57	0.29	2.29	0.34
2.40	0.27	2.13	0.34
2.25	0.26	2.00	0.33
2.12	0.24	1.88	0.32
2.00	0.22	1.78	0.29
1.89	0.20	1.68	0.29
1.80	0.20	1.60	0.25
1.71	0.20	1.52	0.16
1.64	0.20	1.45	0.16
1.57	0.18	1.39	0.16
1.50	0.18	1.33	0.13
1.44	0.16	1.28	0.13
1.38	0.16	1.23	0.12
1.33	0.16	1.19	0.06
1.29	0.14	1.14	0.06
1.24	0.13	1.10	0.06
1.20	0.10	1.07	0.04
1.16	0.093	1.03	0.002
1.12	0.084		
1.09	0.081		
1.06	0.037		
1.03	0.013		

greater than for Walnut Gulch. Beyond the mountains however, the San Simon Wash is generally ephemeral and has low rates of unit runoff where basin area exceeds 1000 km^2. Discharges from small study plots at the Jornada Experimental Range (table 1) may be inadequate to be meaningful and are not included on figure 13. These data however, are consistent with the relation line for small watershed areas of Walnut Gulch.

Although climate and vegetation of the Animas Creek Valley resemble those of the San Simon Wash Basin, basin characteristics and runoff conditions may be similar to those of Walnut Gulch. Specifically, the effects of topography (orographic effects) on precipitation and the resulting runoff to Animas Creek are more like those of Walnut Gulch than to San Simon Wash. The highest point (figure 7) of the Animas Mountains is Animas Peak at 2597 m but, as for Walnut Gulch and the Dragoon Mountains, most mountain areas that contribute runoff to Animas Creek are less than 2000 m in elevation. Animas Creek becomes intermittent

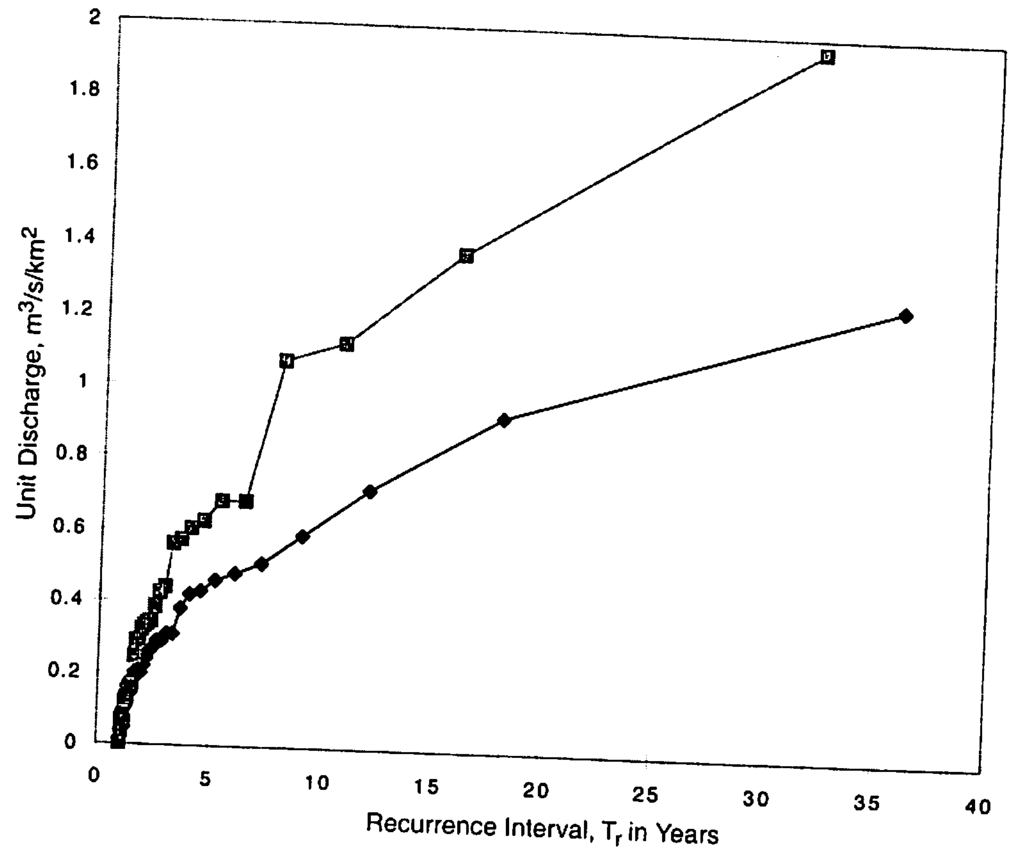

Figure 12—Comparison of unit discharge for annual flood peaks in cubic meters per second per square kilometer ($m^3/s/km^2$) and return period for Animas Creek near Cloverdale, NM (diamonds), and flume 6, Walnut Gulch near Tombstone, AZ (squares).

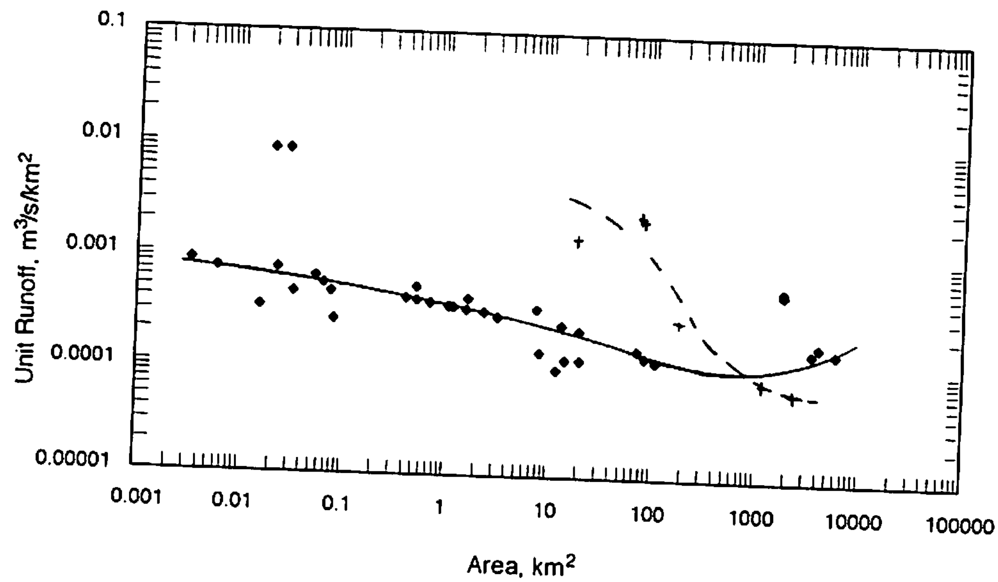

Figure 13—Unit runoff as a function of drainage-basin area for Walnut Gulch and the San Pedro River (series 1), with additional data (+) and a relation line for the San Simon Wash Basin. Relation lines are visual interpretations of best fit.

where the basin area exceeds roughly 500 km^2, whereas Walnut Gulch, except locally, is an ephemeral stream to its confluence with the San Pedro River, where the basin area is about 200 km^2. Almost all of the San Simon Wash, with a drainage area slightly exceeding 5000 km^2 in the lower reaches, has had fully ephemeral streamflow.

Based on the above considerations and recognizing that the elevation of Animas Creek for similar drainage areas is about 300 m greater than that of Walnut Gulch and that precipitation in the Animas Creek Basin averages about 80% of that at Tombstone (table 2), unit runoff for the Animas Creek Basin is inferred to vary with basin area similarly to the Walnut Creek Basin (figure 13). Owing to mountainous parts of the Animas Creek Basin that are generally 10 to 20% higher in elevation than are headwater areas of Walnut Gulch, the mean-runoff curve for Walnut Gulch and the San Pedro River (figure 13) may plot slightly lower for drainage-basin areas of less than about 10 km^2 than would runoff data for the Animas Creek Basin if available. In contrast, for drainage-basin areas of 50 km^2 or more, the data and comparisons of table 5 and figure 12 suggest that an Animas Creek Valley relation might plot slightly lower than the Walnut Gulch/ San Pedro River relation in figure 13.

Erosion and Sediment Yield

Rangeland management, including conservation practices of rotational grazing cycles, during recent decades in the Walnut Gulch Experimental Watershed generally has promoted increased landscape health and stability. The period has been characterized by monsoonal storms of limited areal extent that have not resulted in noteworthy flooding along the Walnut Gulch channel. Fire probably has occurred less frequently than during preceding decades or centuries, allowing the accumulation of sand and gravel in small upland channels that periodically discharge the sediment into Walnut Gulch during local runoff events. No large floods have occurred in Walnut Gulch since 1957. Therefore, the inputs of coarse sediment from tributary basins have caused general channel aggradation during the last 40 y.

Accelerated erosion in the Walnut Gulch and San Simon Wash drainage basins that coincided with and followed periods of drought, catastrophic flooding, and high-intensity grazing occurred primarily in gullies and along channels (Peterson et al. 1960, Graf 1983). In both cases, incision began in lower parts of the drainage network and tended to extend upstream through headcutting. Base-level change by downcutting of the Gila River probably was an insignificant cause of the gully erosion in the San Simon Wash because "... the altitude of the [Gila River] stream-channel floor did not change appreciably during the periods of major stream-channel widening..." (Burkham 1972, p. 12). Post-1880s entrenchment of up to several meters along the San Pedro River (Hereford 1993) however, may have led to headcutting at the mouth of Walnut Gulch.

The deep incision along the San Simon Wash and major tributaries began after weather extremes of the 1880s and probably ceased several decades later. The incision of channels and gullies in the basin, with a total length of nearly 200 km in 1960, caused drainage of near-surface ground-water supplies and greatly reduced the potential for overbank flooding during larger runoff events. This change in basin hydrology was a likely factor in the conversion of valley-floor grassland to dominantly shrubland (Peterson et al. 1960).

With the completion of the Southern Pacific Railroad in 1881, large numbers of cattle were imported into the grasslands of southern Arizona and New Mexico from the central United States, Texas, and California (Sheridan 1995). Owing to its relative isolation and distance from railroads and population centers, landscape stress due to excessive grazing from 1881 to 1940 may have been less pronounced in the upper Animas Creek Basin than it was in the Tombstone and San Simon areas. If so, a possible indication is a lack of significant incision along much of Animas Creek. As in the Walnut Gulch Basin, land-conservation practices of recent decades at the Gray Ranch have been conducive to maintaining rangeland health. Thus, the upper Animas Creek Basin generally exhibits landscape stability, with only local gully erosion being restricted mostly to alluvial swales and valley bottoms of small tributary basins to Animas Creek (K.R. Vincent, National Research Council Associate, oral commun. 1997).

Unlike processes along Walnut Gulch and the San Simon Wash, little or no incision or aggradation has occurred in the Animas Creek channel in the past 40 y. Upland areas of the basin probably sustained less grazing pressure in the preceding decades than at Walnut Gulch and thus, less sediment stored in tributary valleys may have been available for redeposition in Animas Creek. In some upland catchments of the Animas Creek Basin, gully erosion and channel incision is apparent but not extensive. At the 2 small watersheds at the western base of the Animas Mountains that were studied for differences in erosion relative to ground and canopy covers, only 1 showed evidence of recent channel erosion.

Sediment yields from the Walnut Gulch, San Pedro River, and San Simon Creek Basins vary widely with sub-basin and period of record but, for drainage basin areas exceeding 100 km^2, they currently average between 150 and 200 $t/km^2/yr$ (table 4). Owing to similar watershed conditions, but a significantly lower channel gradient relative to runoff, it is anticipated that the present sediment yield for most sites along Animas Creek may fall within or below that range.

Rangeland areas of the Animas Creek Valley have ground- and canopy-cover characteristics approximating those of the Walnut Gulch Basin. Ground cover is nearly unaffected by fire, and canopy cover on most desert rangelands is inadequate to provide significant erosion protection during intense storms. Hence, natural or prescribed range fires may be effective for limiting shrub encroachment but, for a year or more following the fire, a dramatic increase in sediment discharge to and from Animas Creek is unlikely. In contrast, where crown or understory fires occur in pine or juniper woodlands, reduction of canopy cover may lead to short-term increases in sediment yield of 2 to 3 orders of magnitude (P. R. Robichaud, USDA Forest Service, oral commun., 1997). Simulation modelling of pine-forest areas in Idaho, with highly erosive, coarse-textured soils dissimilar to those of the Animas Creek Basin, suggested a 7-fold increase in summer erosion rates following a 30% reduction in canopy cover (Clayton and Megahan 1997).

Gully erosion along Animas Creek during the last century has been insignificant relative to the erosion that occurred in the adjacent San Simon Wash Basin. As suggested, the respective erosion rates were influenced by differences in rainfall, vegetation, elevation, soils, and possibly by accessibility to railroads. At peak intensities, roughly 9 cattle/km^2 grazed the San Simon Valley, but 18 cattle/km^2 grazed the upper Animas Creek Basin. The duration of intense grazing however, was probably significantly longer in the San Simon Wash Basin than in the Animas Valley. Furthermore, the most intense grazing in the Animas Creek Basin did not begin until after the drought and subsequent floods documented by Burkham (1972) for southwestern Arizona in the early part of the century. Thus, grass conditions in the Animas Creek Valley at the time may have been adequate to prevent the start of gully and channel erosion.

Sediment Yield Relative to Drainage-basin Area

Figure 14 relates sediment yields of the Walnut Gulch/San Pedro River system to drainage-basin size. Data are from table 1 and from J. R. Simanton (ARS, written commun. 1994), Renard and Stone (1982), and Simanton et al. (1993). The data plotted in figure 14 do not appear to define a clear trend, but they do suggest that sediment yields in the Walnut Gulch Basin are highest from watersheds about 1 km^2 or slightly less in area. Peak sediment yields from watershed areas of about this size may appear more subdued than the data indicate owing to the logarithmic coordinates of the graph (figure 14). Stream order for the Walnut Gulch Basin, as determined by Miller

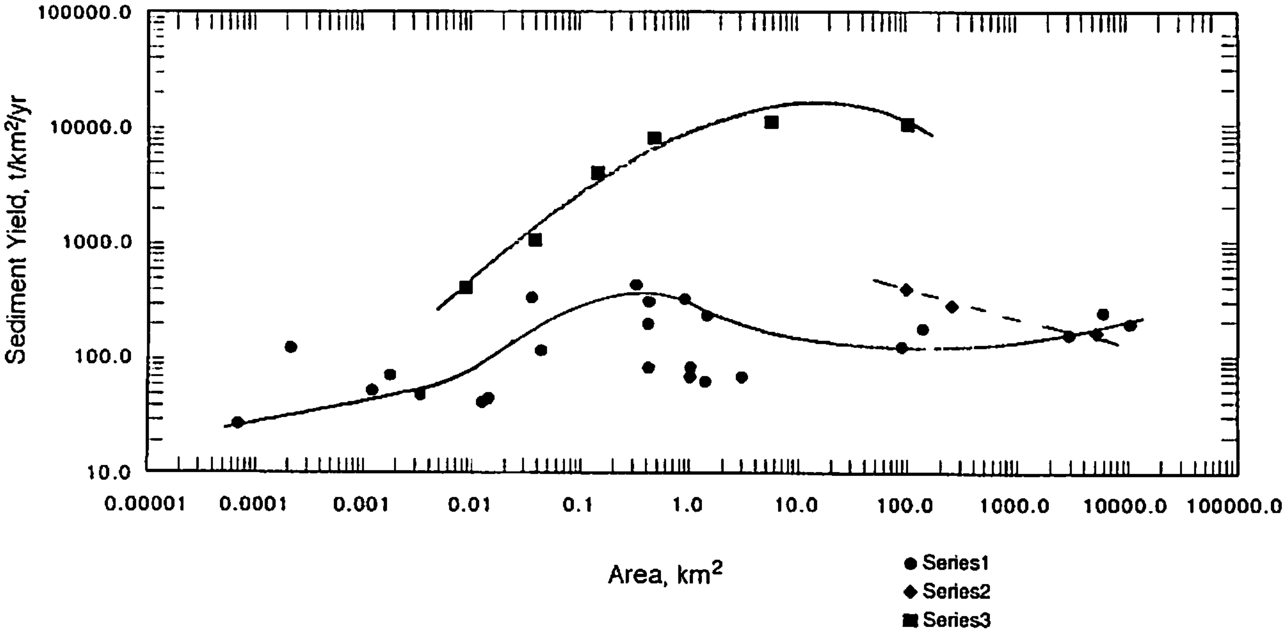

Figure 14—Sediment yield as a function of drainage-basin area for Walnut Gulch/San Pedro River Basin (series 1), with additional data and lines of relation for the San Simon Creek Basin (series 2, dashed line), and a condition of accelerated erosion in the Walnut Gulch Basin (series 3). Relation lines are visual interpretations of best fit.

(1995), ranges between 3 and 4 for watersheds of this size and is indicative of a sufficiently developed stream-channel network that processes bottomland deposition and experiences cyclic incision occur. Not listed in appendix 2 or shown on figure 14 are data from 2 small reservoirs (drainage areas of 1.0 and 1.6 km^2) in the Walnut Gulch Basin (Sedimentation Committee, Water Resources Council 1977). Sediment yields computed from surveys of the reservoirs averaged about 120 and 140 t/km^2/yr, respectively, during 10- to 12-y periods, which seem consistent with other data summarized in figure 14.

Sediment-yield data from plot studies at Jornada Experimental Range (Bolin and Ward 1987) total 16 y of record (table 1). These data are not plotted on figure 14, but the average value of sediment yield derived from the research, 27.1 t/km^2/yr, seems compatible with the drainage-area/sediment-yield relation developed for Walnut Gulch.

With increasing basin size from 1 km^2, depositional processes appear to exceed the rate of sediment delivery to the channel network, and sediment yield declines with increasing basin size. For conditions of consistent vegetation cover, this trend may be most pronounced for watershed sizes of 10 to 100 km^2 in which bottomland alluvial deposits are of sufficient volume that transmission loss during flow events causes deposition of sediment and reduced sediment yield. In addition, where drainage-basin size exceeds the typical area of intense rainfall during convectional storms, yields of runoff and sediment may be largely depleted by transmission loss. The data points for lower Walnut Gulch and the San Pedro River (5 data points of series 1, right side of graph, figure 14) probably plot high owing to sediment discharges related to long-term grazing in the basin.

Another second sediment-yield curve for Walnut Gulch (series 3, figure 14) is based on data modified from Graf (1983). These data are representative of a period, mostly in the 1930s, when pronounced gully and channel erosion in parts of the Walnut Gulch Basin caused evacuation of stored alluvium rather than additional deposition of sediment in bottomlands of watersheds greater than 1 km^2. Thus, peak sediment yields suggested by data from Graf (1983) are translocated to a drainage-basin about 20 km^2 (figure 14), the size at which the sum of rill, gully, and other upland erosion processes become balanced by storage of the eroded sediment in alluvial bottomlands.

Based on limited data for sediment deposition in 2 reservoirs and a 23-y sediment-yield record for the San Simon Creek or River near Solomon, during a period of accelerated gully erosion (table 1, appendix 2), a relation between sediment yield and drainage area is interpreted for stressed conditions in the San Simon Wash Basin (figure 14). The relation line may under-represent sediment yield for the basin significantly during disturbed conditions. Both reservoirs, Creighton and H-X, impounded water and sediment of Gold Gulch, a major tributary to the San Simon Wash from the southwest. Headwaters of Gold Gulch are in the northern Dos Cabezas Mountains, a bedrock area less vulnerable to pronounced gullying than is the alluvium of the valley, and data sets for both reservoirs are for 1956 through 1958, after the most active gully erosion of the San Simon Wash Basin. Calculated sediment yields for H-X Reservoir (table 1, appendix 2), the lower reservoir of the San Simon Wash, were calculated using the contributing drainage area between the reservoirs. The sediment-discharge records collected for the San Simon River near Solomon include years of active gully erosion, but the station is below the part of the basin where the gullying was most pronounced; hence, the records may reflect periods of both erosion and local deposition.

Comparing the curves of figure 14, (series 1 and 3) peak sediment yield, for recent decades from small, relatively unstressed watersheds of the Walnut Gulch Basin, has been about 400 t/km^2/yr; whereas, sediment yield during a period of accelerated channel incision reached roughly 100,000 t/km^2/yr and occurred in watersheds of about 10 or 20 km^2. Many other studies in various climatic conditions (e.g., Wolman 1967, Meade and Parker 1985) have also indicated that sediment yield typically increases by 1 to 3 orders of magnitude during periods of surface disturbance.

Although current watershed conditions in the Walnut Gulch Basin do not generally exhibit significant disturbance, partial conversion from grassland to shrubland in the basin during the last 100 y suggests that present sediment yields may be higher than those before the influx of cattle. The sediment-yield curve for the San Simon Wash Basin is based on only 3 data sets of questionable reliability, has been drawn to conform partially with more credible accelerated-erosion data of the Walnut Gulch drainage network, and probably denotes sediment-yield rates lower than those that prevailed during the 1930s and 1940s.

The curves of figure 14, modified by observations of differences in geology and soils, topography, vegetation, climate, and hydrology in the several basins, suggest that recent sediment yields in the Animas Creek Basin have not been elevated notably from the long-term average and do not represent accelerated erosion. Sediment yield relative to drainage area in the Animas Creek Basin (the shape of the curve) probably is similar to that for relatively stable conditions in the Walnut Gulch Basin. Because the Animas Creek Basin is generally grassland draining to base levels of erosion (playas), sediment yields from watersheds of most sizes are probably lower than those from watersheds of similar size in the Walnut Gulch Basin. If accelerated gully erosion were to begin in the Animas Creek Basin, sediment yields, relative to drainage area, could rapidly increase and approximate those indicated for accelerated erosion in the Walnut Gulch Basin.

Discussion and Summary

Runoff characteristics in the Animas Creek Basin appear to be similar to those of the Walnut Gulch Basin, ranging from roughly 1×10^{-4} m^3/sec/km^2 from a basin area of 100 km^2 to about 3×10^{-4} m^3/sec/km^2 from subwatersheds of 1 to 5 km^2. These rates may be largely unchanged from predevelopment conditions. Owing to relatively high runoff rates from areas of bedrock exposures in mountains bounding the Animas Valley, unit runoff from watersheds smaller than 1 km^2 may be generally greater than for otherwise comparable alluvial uplands of the Walnut Gulch Basin.

Sediment yield, as a function of watershed area in the Animas Valley, is inferred to be lower than for the Walnut Gulch Basin. This interpretation is based on the assumption that runoff characteristics from the 2 basins are similar, but the vegetation cover in the Animas Valley, dominated by grasses, provides better protection against erosion than is available to shrublands of greater topographic relief that are typical of the Walnut Gulch Basin. If, as a result of causes such as excessive grazing, fire, or climate change, grassland of the Animas Creek Basin converts to shrubland, gully erosion in various parts of the drainage network is likely to increase and sediment yields could increase as much as 3 orders of magnitude.

Channel gradients of Animas Creek and San Simon Wash are similar but lower than that of Walnut Gulch. The relatively high channel gradient of Walnut Gulch increased the susceptibility to channel and gully erosion in the first half of the century; whereas, the soils, topography, and grazing history relative to drought and storms may have contributed to pronounced gully erosion along the San Simon Wash. The level of Animas Creek is partially controlled by the positions of fan deposits and playa-lake basins, and accordingly Animas Creek in recent decades and centuries probably has not been prone to the gullying and channel erosion that occurred along Walnut Gulch and San Simon Wash.

If, owing to future changes in factors such as land use, vegetation, fire frequency, or climate, tributary and upland erosion in the upper Animas Creek Basin increases, aggradation in the Animas Creek channel will likely result. Animas Creek has not been and presently is not subject to the same base-level conditions that probably led to erosion in drainage networks of other Southwestern watersheds. If upland rill and interrill erosion results in significantly increased sediment yield in the upper Animas Valley, much of the sediment will probably be deposited along Animas Creek, and most will likely remain in the Gray Ranch area.

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Appendix 1. Dominant plants in the Walnut Gulch Experimental Watershed

acacia	*Acacia* spp.
agave	*Agave* spp.
beargrass	*Nolina texana* Wats.
black grama	*Bouteloua eriopoda* Torr.
blue grama	*Bouteloua gracilis* (H.B.K.)
buffalo grass	*Buchloe dactyloides* (Nutt.)
burrograss	*Scleropogon brevifoluis* Phil.
burroweed	*Aplopappus tenuisectus* (Greene)
catclaw	*Acacia greggii* Gray.
chamiso	*Atriplex canescens* (Pursh.) Nutt.
cholla	*Opuntia* spp.
creosotebush	*Larrea tridentata* (DC.)
curly mesquite	*Hilaria belangeri* (Steud.) Nash
desert willow	*Chilopsis linearis* (Cav.) Sweet.
Emory oak	*Quercus emoryi* Torr.
golden eye	*Viguiera* spp.
hairy grama	*Bouteloua hirsuta* Lag.
juniper	*Juniperus deppeana* Steud.
Lehmann lovegrass	*Eragrostis lehmanniana* Nees.
mesquite	*Prosopis* spp.
Mormon tea	*Ephedra californica* S.Watson
mortonia	*Mortonia scabrella* Gray.
mountain mahogany	*Cercocarpus* spp.
pinyon pine	*Pinus edulis* Engelm.
ponderosa pine	*Pinus ponderosa* Larson
rabbitbrush	*Chrysothamnus* spp.
Russian thistle	*alsola kali* L.
sacaton	*Sporobolus wrightii* Munro.
sideoats grama	*Bouteloua curtipendula* (Michx.)
silverleaf oak	*Quercus hypoleucoides* Camus
snakeweed	*Gutierrezia* spp.
soaptree yucca	*Yucca elata* Engelm.
sotol	*Dasylirion wheeleri* Wats.
tarbush	*Flourensia cernua* DC.
tobosa	*Hilaria mutica* (Buchl.)
white-thorn	*Acacia constricta* Benth.
yucca	*Yucca* spp.

Appendix 2. Tabulations of annual runoff and sediment-discharge data (flumes 101-106) for sites in the Walnut Gulch/San Pedro River and San Simon Wash drainage basins.

Flume 1 — Walnut Gulch, Tombstone, AZ drainage area 149 km^2

Year	Mean runoff m^3/s	Unit discharge $m^3/s/km^2$
1957	0.0584	0.000392
1958	0.0280	0.000188
1959	0.0221	0.000148
1960	0.0002	0.000001
1961	0.0317	0.000213
1962	0.0213	0.000143
1963	0.0572	0.000384
1964	0.0548	0.000367
1965	0.0044	0.000030
1966	0.0169	0.000113
1967	0.0163	0.000109
1968	0.0070	0.000047
1969	0.0093	0.000062
1970	0.0112	0.000075
1971	0.0276	0.000185
1972	0.0202	0.000135
1973	0.0089	0.000060
1974	0.0092	0.000061
1975	0.0196	0.000132
1976	0.0129	0.000086
1977	0.0226	0.000151
1978	0.0029	0.000020
1979	0.0000	0.000000
1980	0.0017	0.000011
1981	0.0165	0.000111
1982	0.0233	0.000156
1983	0.0198	0.000133
1984	0.0047	0.000031
1985	0.0052	0.000035
1986	0.0099	0.000067
1987	0.0019	0.000013
1988	0.0022	0.000015
1989	0.0007	0.000004
1990	0.0225	0.000151
1991	0.0041	0.000028
1992	0.0018	0.000012
Total	0.5770	0.003869
Average	0.0103	0.000107

Flume 2—Walnut Gulch, Tombstone, AZ drainage area 114 km²

Year	Mean runoff m³/s	Unit runoff m³/s/km²
1959	0.0335	0.000294
1960	0.0005	0.000005
1961	0.0290	0.000255
1962	0.0156	0.000137
1963	0.0230	0.000202
1964	0.0470	0.000412
1965	0.0065	0.000057
1966	0.0163	0.000143
1967	0.0158	0.000138
1968	0.0057	0.000050
1969	0.0011	0.000007
1970	0.0188	0.000165
1971	0.0356	0.000312
1972	0.0106	0.000093
1973	0.0039	0.000034
1974	0.0136	0.000119
1975	0.0263	0.000231
1976	0.0150	0.000132
1977	0.0198	0.000173
1978	0.0050	0.000044
1979	0.0000	0.000000
1980	0.0024	0.000021
1981	0.0158	0.000139
1982	0.0229	0.000201
1983	0.0198	0.000173
1984	0.0045	0.000039
1985	0.0076	0.000066
1986	0.0090	0.000079
1987	0.0014	0.000012
1988	0.0036	0.000032
1989	0.0010	0.000009
1990	0.0165	0.000145
1991	0.0027	0.000023
1992	0.0027	0.000024
Total	0.4525	0.003966
Average	0.0133	0.000117

Flume 3—Walnut Gulch, Tombstone, AZ drainage area 8.98 km²

Year	Mean runoff m³/s	Unit runoff m³/s/km²
1958	0.00507	0.000564
1959	0.00057	0.000064
1960	0.00004	0.000004
1961	0.00281	0.000313
1962	0.00060	0.000066

Flume 3—Walnut Gulch, Tombstone, AZ drainage area 8.98 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1963	0.00040	0.000044
1964	0.00305	0.000339
1965	0.00036	0.000041
1966	0.00025	0.000028
1967	0.00024	0.000026
1968	0.00026	0.000029
1969	0.00003	0.000004
1970	0.00143	0.000160
1971	0.00433	0.000482
1972	0.00019	0.000021
1973	0.00018	0.000020
1974	0.00049	0.000055
1975	0.00347	0.000387
1976	0.00015	0.000017
1977	0.00401	0.000447
1978	0.00010	0.000012
1979	0.00000	0.000000
1980	0.00026	0.000029
1981	0.00082	0.000091
1982	0.00094	0.000105
1983	0.00205	0.000228
1984	0.00147	0.000164
1985	0.00085	0.000094
1986	0.00043	0.000048
1987	0.00054	0.000060
1988	0.00042	0.000047
1989	0.00001	0.000001
1990	0.00220	0.000254
1991	0.00083	0.000092
1992	0.00025	0.000028
Total	0.03910	0.004364
Average	0.00112	0.000125

Flume 4—Walnut Gulch, Tombstone, AZ drainage area 2.27 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1954	0.00232	0.00102
1955	0.00973	0.00429
1956	0.00030	0.00013
1957	0.00030	0.00013
1958	0.00068	0.00030
1961	0.00102	0.00045
1962	0.00010	0.00005
1963	0.00007	0.00003
1964	0.00070	0.00031

Flume 4—Walnut Gulch, Tombstone, AZ drainage area 2.27 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1965	0.00001	0.00001
1966	0.00003	0.00001
1967	0.00005	0.00002
1968	0.00007	0.00003
1969	0.00000	0.00000
1970	0.00041	0.00018
1971	0.00215	0.00095
1972	0.00009	0.00004
1973	0.00015	0.00007
1974	0.00028	0.00012
1975	0.00080	0.00035
1976	0.00005	0.00002
1977	0.00149	0.00065
1978	0.00011	0.00005
1979	0.00001	0.00000
1980	0.00011	0.00005
1981	0.00034	0.00015
1982	0.00041	0.00018
1983	0.00030	0.00013
1984	0.00067	0.00030
1985	0.00032	0.00014
1986	0.00030	0.00013
1987	0.00016	0.00007
1988	0.00019	0.00008
1989	0.00001	0.00000
1990	0.00112	0.00049
1991	0.00033	0.00014
1992	0.00012	0.00005
Total	0.02530	0.01112
Average	0.00068	0.000301

Flume 6—Walnut Gulch, Tombstone, AZ drainage area 95.1 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1962	0.0163	0.000172
1963	0.0270	0.000283
1964	0.0576	0.000606
1965	0.0079	0.000083
1966	0.0206	0.000216
1967	0.0201	0.000211
1968	0.0050	0.000053
1969	0.0016	0.000017
1970	0.0150	0.000158
1971	0.0292	0.000307
1972	0.0080	0.000084

Flume 6—Walnut Gulch, Tombstone, AZ drainage area 95.1 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1973	0.0009	0.000010
1974	0.0134	0.000141
1975	0.0202	0.000212
1976	0.0168	0.000176
1977	0.0165	0.000174
1978	0.0062	0.000065
1979	0.0000	0.000000
1980	0.0027	0.000029
1981	0.0197	0.000207
1982	0.0262	0.000276
1983	0.0204	0.000214
1984	0.0037	0.000039
1985	0.0078	0.000082
1986	0.0109	0.000115
1987	0.0019	0.000020
1988	0.0041	0.000043
1989	0.0010	0.000011
1990	0.0168	0.000177
1991	0.0011	0.000011
1992	0.0028	0.000030
Total	0.4014	0.004222
Average	0.0129	0.000136

Flume 7—Walnut Gulch, Tombstone, AZ drainage area 13.5 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1966	0.00139	0.000103
1967	0.00086	0.000064
1968	0.00126	0.000093
1969	0.00116	0.000086
1970	0.00007	0.000005
1971	0.00077	0.000057
1972	0.00482	0.000357
1973	0.00444	0.000329
1974	0.00160	0.000119
1975	0.00022	0.000016
1976	0.00032	0.000023
1977	0.00311	0.000230
1978	0.00003	0.000002
1979	0.00003	0.000002
1980	0.00023	0.000017
1981	0.00292	0.000216
1982	0.00190	0.000141
1983	0.00143	0.000106

Flume 7—Walnut Gulch, Tombstone, AZ drainage area 13.5 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1984	0.00036	0.000027
1985	0.00010	0.000007
1986	0.00094	0.000069
1987	0.00000	0.000000
1988	0.00069	0.000051
1989	0.00003	0.000003
1990	0.00182	0.000135
1991	0.00054	0.000040
1992	0.00039	0.000030
Total	0.03143	0.002328
Average	0.00116	0.000086

Flume 8—Walnut Gulch, Tombstone, AZ drainage area 15.5 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1963	0.00487	0.000323
1964	0.01121	0.000723
1965	0.00420	0.000271
1966	0.00355	0.000229
1967	0.00893	0.000576
1968	0.00120	0.000077
1969	0.00100	0.000064
1970	0.00428	0.000276
1971	0.00602	0.000388
1972	0.00094	0.000061
1973	0.00142	0.000092
1974	0.00108	0.000070
1975	0.00933	0.000602
1976	0.00350	0.000226
1977	0.00493	0.000318
1978	0.00187	0.000120
1979	0.00005	0.000003
1980	0.00131	0.000085
1981	0.00233	0.000150
1982	0.00622	0.000402
1983	0.00853	0.000550
1984	0.00133	0.000086
1985	0.00049	0.000031
1986	0.00564	0.000364
1987	0.00085	0.000055
1988	0.00065	0.000042
1989	0.00030	0.000019
Total	0.09603	0.006203
Average	0.00356	0.000230

Flume 9—Walnut Gulch, Tombstone, AZ drainage area 23.6 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1967	0.00868	0.000368
1968	0.00021	0.000009
1969	0.00103	0.000044
1970	0.00793	0.000336
1971	0.01478	0.000626
1972	0.01134	0.000481
1973	0.00003	0.000001
1974	0.00744	0.000315
1975	0.00763	0.000323
1976	0.00853	0.000361
1977	0.00398	0.000168
1978	0.00371	0.000157
1979	0.00019	0.000008
1980	0.00113	0.000048
1981	0.00923	0.000391
1982	0.00873	0.000370
1983	0.00552	0.000234
1984	0.00190	0.000081
1985	0.00519	0.000220
1986	0.00430	0.000182
1987	0.00017	0.000007
1988	0.00177	0.000075
1989	0.00131	0.000055
1990	0.00785	0.000333
1991	0.00095	0.000040
1992	0.00181	0.000077
Total	0.12534	0.005310
Average	0.00482	0.000204

Flume 10—Walnut Gulch, Tombstone, AZ drainage area 16.6 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1967	0.00578	0.000348
1968	0.00002	0.000001
1969	0.00017	0.000010
1970	0.00197	0.000119
1971	0.00361	0.000218
1972	0.00116	0.000070
1973	0.00003	0.000002
1974	0.00226	0.000136
1975	0.00271	0.000163
1976	0.00613	0.000369
1977	0.00169	0.000102
1978	0.00112	0.000067

Flume 10—Walnut Gulch, Tombstone, AZ drainage area 16.6 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1979	0.00000	0.000000
1980	0.00145	0.000087
1981	0.00295	0.000178
1982	0.00442	0.000266
1983	0.00226	0.000136
1984	0.00055	0.000033
1985	0.00121	0.000073
1986	0.00328	0.000198
1987	0.00031	0.000019
1988	0.00053	0.000032
1989	0.00048	0.000029
1990	0.00159	0.000096
1991	0.00017	0.000010
1992	0.00039	0.000023
Total	0.04624	0.002785
Average	0.00178	0.000107

Flume 11—Walnut Gulch, Tombstone, AZ drainage area 8.23 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1963	0.00236	0.000287
1964	0.01977	0.002402
1965	0.00513	0.000624
1966	0.00366	0.000445
1967	0.00514	0.000625
1968	0.00172	0.000210
1969	0.00080	0.000098
1970	0.00250	0.000304
1971	0.00290	0.000352
1972	0.00072	0.000088
1973	0.00190	0.000231
1974	0.00048	0.000059
1975	0.00536	0.000652
1976	0.00207	0.000251
1977	0.00433	0.000526
1978	0.00082	0.000099
1979	0.00002	0.000002
1980	0.00115	0.000140
1981	0.00144	0.000175
1982	0.00707	0.000859
1983	0.00217	0.000263
1984	0.00038	0.000047
1985	0.00052	0.000063
1986	0.00382	0.000464

Flume 11—Walnut Gulch, Tombstone, AZ drainage area 8.23 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1987	0.00009	0.000011
1988	0.00040	0.000049
1989	0.00069	0.000084
1990	0.00236	0.000287
1991	0.00020	0.000025
1992	0.00035	0.000043
Total	0.08032	0.009765
Average	0.00268	0.000326

Flume 15—Walnut Gulch, Tombstone, AZ drainage area 23.9 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1965	0.00163	0.000068
1966	0.00748	0.000313
1967	0.00618	0.000259
1968	0.00427	0.000179
1969	0.00001	0.000001
1970	0.00419	0.000175
1971	0.00684	0.000286
1972	0.00064	0.000027
1973	0.00033	0.000014
1974	0.00668	0.000280
1975	0.00256	0.000107
1976	0.00360	0.000151
1977	0.00443	0.000185
1978	0.00124	0.000052
1979	0.00003	0.000001
1980	0.00000	0.000000
1981	0.00203	0.000085
1982	0.00402	0.000168
1983	0.00563	0.000236
1984	0.00037	0.000015
1985	0.00138	0.000058
1986	0.00096	0.000040
1987	0.00000	0.000000
1988	0.00249	0.000104
1989	0.00011	0.000005
1990	0.00360	0.000151
1991	0.00000	0.000000
1992	0.00112	0.000047
Total	0.07182	0.003007
Average	0.00256	0.000107

Flume 101—Walnut Gulch, Tombstone, AZ drainage area 0.0129 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1962	0.00000151	0.000117	
1963	0.00001522	0.001180	
1964	0.00001996	0.001548	
1965	0.00002162	0.001676	
1966	0.00000650	0.000504	
1967	0.00000582	0.000452	
1968	0.00000716	0.000555	
1969	0.00000248	0.000192	
1970	0.00000920	0.000713	
1971	0.00002054	0.001592	
1972	0.00000665	0.000516	15.3
1973	0.00000792	0.000614	19.6
1974	0.00001097	0.000850	114.9
1975	0.00003388	0.002626	50.5
1976	0.00000561	0.000435	140.1
1977	0.00002466	0.001911	7.8
1978	0.00000728	0.000564	0.0
1979	0.00000039	0.000030	2.5
1980	0.00000099	0.000076	17.3
1981	0.00000920	0.000713	
1982	0.00000753	0.000584	
1983	0.00000476	0.000369	
1984	0.00001379	0.001069	
1985	0.00000118	0.000091	
1986	0.00000429	0.000333	
Total	0.00024911	0.019310	368.0
Average	0.00001000	0.009660	40.9

Flume 102/102.1—Walnut Gulch, Tombstone, AZ drainage area 0.0146 km² (1976/1977)

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1963	0.00001155	0.000791	
1964	0.00002284	0.001564	
1965	0.00000816	0.000559	
1966	0.00000236	0.000162	
1967	0.00000430	0.000294	
1968	0.00000712	0.000488	
1969	0.00000112	0.000077	
1970	0.00000861	0.000590	
1971	0.00001760	0.001205	
1972	0.00001001	0.000686	0.1
1973	0.00001241	0.000850	
1974	0.00001365	0.000935	
1975	0.00002913	0.001995	

Flume 102/102.1—Walnut Gulch, Tombstone, AZ drainage area 0.0146 km^2 (1976/1977)

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1976	0.00000445	0.000305	
1977	0.00002378	0.001628	83.3
1978	0.00000406	0.000278	49.1
1979	0.00000097	0.000067	
1980	0.00000177	0.000121	
1981	0.00001076	0.000737	
1982	0.00000930	0.000637	
1983	0.00000970	0.000664	
1984	0.00002768	0.001896	
1985	0.00001400	0.000959	
1986	0.00001156	0.000792	
1987	0.00000309	0.000212	
1988	0.00000042	0.000029	
1989	0.00000165	0.000113	
1990	0.00002537	0.001738	
1991	0.00001286	0.000881	
1992	0.00001176	0.000806	
Total	0.00032204	0.022059	132.5
Average	0.00001074	0.000735	44.2

Flume 103—Walnut Gulch, Tombstone, AZ drainage area 0.0368 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1963	0.0000262	0.000712	
1964	0.0000328	0.000891	
1965	0.0000178	0.000484	
1966	0.0000160	0.000433	
1967	0.0000114	0.000309	
1968	0.0000166	0.000452	
1969	0.0000045	0.000123	
1970	0.0000237	0.000645	
1971	0.0000345	0.000935	
1972	0.0000216	0.000587	130.1
1973	0.0000194	0.000528	278.0
1974	0.0000258	0.000701	486.0
1975	0.0000703	0.001912	859.0
1976	0.0000131	0.000356	242.0
1977	0.0000604	0.001642	681.0
1978	0.0000121	0.000330	200.0
1979	0.0000017	0.000046	47.0
1980	0.0000036	0.000097	56.0
1981	0.0000266	0.000724	
1982	0.0000181	0.000491	
1983	0.0000212	0.000575	
1984	0.0000453	0.001230	

Flume 103—Walnut Gulch, Tombstone, AZ drainage area 0.0368 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1985	0.0000205	0.000558	
1986	0.0000204	0.000554	
1987	0.0000042	0.000115	
1988	0.0000124	0.000336	
1989	0.0000028	0.000076	
1990	0.0000536	0.001455	
1991	0.0000253	0.000689	
1992	0.0000295	0.000803	
Total	0.0006914	0.018789	2979.1
Average	0.0000230	0.000626	331.0

Flume 104—Walnut Gulch, Tombstone, AZ drainage area 0.0453 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1963	0.0000298	0.000658	
1964	0.0000453	0.000999	
1965	0.0000235	0.000518	
1966	0.0000086	0.000189	
1967	0.0000068	0.000151	
1968	0.0000109	0.000241	
1969	0.0000037	0.000082	
1970	0.0000199	0.000438	
1971	0.0000535	0.001181	
1972	0.0000232	0.000512	57.0
1973	0.0000260	0.000574	78.0
1974	0.0000421	0.000930	168.0
1975	0.0000789	0.001742	318.0
1976	0.0000082	0.000182	70.0
1977	0.0000444	0.000980	298.0
1978	0.0000052	0.000114	18.0
1979	0.0000014	0.000031	0.0
1980	0.0000038	0.000085	22.0
1981	0.0000267	0.000589	
1982	0.0000238	0.000526	
1983	0.0000184	0.000406	
1984	0.0000539	0.001190	
1985	0.0000205	0.000453	
1986	0.0000195	0.000431	
1987	0.0000033	0.000072	
1988	0.0000106	0.000234	
1989	0.0000022	0.000048	
1990	0.0000708	0.001562	
1991	0.0000278	0.000614	
1992	0.0000196	0.000433	
Total	0.0007323	0.016165	1029.0
Average	0.0000244	0.000539	114.3

Flume 105—Walnut Gulch, Tombstone, AZ drainage area 0.00182 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1965	0.00000103	0.000568	
1966	0.00000098	0.000537	
1967	0.00000117	0.000642	
1968	0.00000125	0.000686	
1969	0.00000043	0.000237	
1970	0.00000125	0.000686	
1971	0.00000298	0.001637	
1972	0.00000120	0.000659	
1973	0.00000150	0.000827	0.3
1974	0.00000180	0.000992	249.4
1975	0.00000507	0.002786	39.6
1976	0.00000082	0.000453	97.0
1977	0.00000272	0.001493	24.1
1978	0.00000061	0.000334	
1979	0.00000011	0.000060	
1980	0.00000023	0.000125	7.0
1981	0.00000173	0.000950	
1982	0.00000138	0.000758	
1983	0.00000146	0.000802	
1984	0.00000354	0.001942	
1985	0.00000142	0.000781	
1986	0.00000181	0.000994	
1992	0.00000159	0.000871	
Total	0.00003608	0.019820	417.4
Average	0.00000157	0.000862	69.6

Flume 106—Walnut Gulch, Tombstone, AZ drainage area 0.00344 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1965	0.00000175	0.000508	
1966	0.00000125	0.000364	
1967	0.00000081	0.000234	
1968	0.00000150	0.000437	
1969	0.00000068	0.000197	
1970	0.00000219	0.000636	
1971	0.00000563	0.001636	
1972	0.00000173	0.000503	
1973	0.00000222	0.000644	
1974	0.00000343	0.000998	81.0
1975	0.00000791	0.002298	15.3
1976	0.00000100	0.000292	59.7
1977	0.00000522	0.001518	7.6
1978	0.00000072	0.000209	
1979	0.00000018	0.000052	1.7

Flume 106—Walnut Gulch, Tombstone, AZ drainage area 0.00344 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1980	0.00000046	0.000135	118.5
1981	0.00000345	0.001004	
1982	0.00000368	0.001071	
1983	0.00000329	0.000957	
1984	0.00000650	0.001889	
1985	0.00000260	0.000755	
1986	0.00000213	0.000619	
1987	0.00000021	0.000060	
1988	0.00000067	0.000195	
1989	0.00000015	0.000044	
1990	0.00000638	0.001856	
1991	0.00000266	0.000773	
1992	0.00000256	0.000745	
Total	0.00007096	0.020629	283.8
Average	0.00000253	0.000737	47.3

Flume 112—Walnut Gulch, Tombstone, AZ drainage area 0.0186 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1962	0.0000121	0.000648
1963	0.0000233	0.001254
1964	0.0000508	0.002729
1965	0.0000106	0.000567
1966	0.0000286	0.001538
1967	0.0000022	0.000117
1968	0.0000005	0.000026
1969	0.0000049	0.000265
1970	0.0000166	0.000892
1971	0.0000076	0.000410
1972	0.0000128	0.000688
1973	0.0000002	0.000009
1974	0.0000064	0.000344
1975	0.0000064	0.000343
1976	0.0000338	0.001820
1977	0.0000107	0.000575
1978	0.0000008	0.000044
1979	0.0000001	0.000004
1980	0.0000122	0.000656
1981	0.0000130	0.000698
1982	0.0000367	0.001973
1983	0.0000251	0.001347
1984	0.0000061	0.000327
1985	0.0000055	0.000296
1986	0.0000157	0.000847

Flume 112—Walnut Gulch, Tombstone, AZ drainage area 0.0186 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1990	0.0000071	0.000382
1991	0.0000103	0.000555
1992	0.0000011	0.000061
Total	0.0003612	0.019415
Average	0.0000129	0.009710

Flume 121—Walnut Gulch, Tombstone, AZ drainage area 0.0542 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1972	0.0000125	0.000232
1973	0.0000077	0.000142
1974	0.0000219	0.000404
1975	0.0000501	0.000924
1976	0.0000048	0.000089
1977	0.0000573	0.001057
1978	0.0000092	0.000169
1979	0.0000087	0.000161
1980	0.0000174	0.000321
1981	0.0000310	0.000572
1982	0.0000292	0.000540
1983	0.0000821	0.000152
1984	0.0000389	0.000718
1985	0.0000407	0.000752
1986	0.0000271	0.000499
1987	0.0000103	0.000190
1988	0.0000236	0.000436
1989	0.0000010	0.000018
1990	0.0000776	0.001432
1991	0.0000190	0.000350
1992	0.0000135	0.000250
Total	0.0005836	0.009408
Average	0.0000278	0.000448

Flume 122—Walnut Gulch, Tombstone, AZ drainage area 0.00971 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1974	0.00000036	0.000037
1975	0.00000311	0.000320
1976	0.00000390	0.000402
1977	0.00000672	0.000692
1978	0.00000156	0.000161
1979	0.00000071	0.000073
1980	0.00000037	0.000038

Flume 122—Walnut Gulch, Tombstone, AZ drainage area 0.00971 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1981	0.00000393	0.000407
1982	0.00000496	0.000511
1983	0.00000648	0.000667
1984	0.00000447	0.000461
1985	0.00000198	0.000204
1986	0.00000200	0.000206
Total	0.00004055	0.004179
Average	0.00000312	0.000321

Flume 124—Walnut Gulch, Tombstone, AZ drainage area 0.0218 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1974	0.00000088	0.000040
1975	0.00000838	0.000384
1976	0.00000772	0.000354
1977	0.00000729	0.000334
1978	0.00000600	0.000275
1979	0.00000053	0.000024
1980	0.00000201	0.000092
1981	0.00001165	0.000534
1982	0.00001732	0.000794
1983	0.00002337	0.001072
1984	0.00002074	0.000952
1985	0.00000888	0.000407
1986	0.00001545	0.000709
1987	0.00001283	0.000589
1988	0.00000833	0.000382
1989	0.00000009	0.000004
1990	0.00002414	0.001107
1991	0.00000074	0.000034
1992	0.00000706	0.000328
Total	0.00018341	0.008415
Average	0.00000965	0.000443

Flume 125—Walnut Gulch, Tombstone, AZ drainage area 0.0591 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1981	0.0000448	0.000758
1982	0.0000036	0.000060
1983	0.0000174	0.000295
1984	0.0000173	0.000293
1985	0.0000187	0.000316
1986	0.0000004	0.000006

Flume 125—Walnut Gulch, Tombstone, AZ drainage area 0.0591 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1987	0.0000019	0.000032
1988	0.0000096	0.000162
1989	0.0000002	0.000004
1990	0.0000203	0.000343
1991	0.0000369	0.000624
1992	0.0000016	0.000028
Total	0.0001727	0.002921
Average	0.0000144	0.000243

East Turkey Creek at Paradise, AZ drainage area 21.2 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1920	0.0742210	0.003501
1921	0.0563739	0.002659
1922	0.0022663	0.000107
1923	0.0305949	0.001443
1924	0.0280453	0.001323
1925	0.0005666	0.000027
Total	0.1920680	0.009060
Average	0.0320113	0.001510

San Simon Creek near San Simon, AZ drainage area 2106 km²

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1920	0.2067988	0.000098
1921	0.5807365	0.000275
1922	0.1784702	0.000085
1923	0.0376705	0.000179
1924	0.0368271	0.000017
1925	0.0226628	0.000011
1932	0.0263456	0.000012
1933	0.0405099	0.000019
1936	0.1133144	0.000054
1937	0.0141643	0.000007
1938	0.0679886	0.000032
1939	0.1019830	0.000048
1940	0.2379603	0.000113
Total	1.6654320	0.000950
Average	0.1281101	0.000073

Cave Creek near Paradise, AZ drainage area 101 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$
1920	0.5635	0.0055788
1921	0.2368	0.0023448
1922	0.0663	0.0006563
1923	0.2479	0.0024542
1924	0.3751	0.0037136
1925	0.0246	0.0002440
Total	1.5142	0.0149917
Average	0.2524	0.0024986

San Simon River near Solomon, AZ drainage area 5677 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1936	0.5322	0.0000937	204.5
1937	0.1017	0.0000179	49.4
1938	0.2209	0.0000389	124.5
1939	0.1259	0.0000222	82.7
1940	0.4743	0.0000835	151.3
1941	0.5169	0.0000911	197.5
1942	0.3335	0.0000588	119.2
1943	0.6358	0.0001120	216.0
1944	0.6534	0.0001151	243.1
1945	0.3214	0.0000566	160.6
1946	0.2522	0.0000444	43.7
1947	0.1584	0.0000279	59.9
1948	0.1822	0.0000321	69.6
1949	0.5701	0.0001004	204.2
1950	0.2205	0.0000388	80.7
1951	0.2209	0.0000391	103.7
1952	0.2624	0.0000462	74.2
1953	0.2502	0.0000441	166.0
1954	1.0784	0.0001900	387.4
1955	0.9901	0.0001760	381.8
1956	0.1282	0.0000226	19.3
1957	0.7914	0.0001394	288.0
1958	0.3382	0.0000596	244.0
1959	0.3705	0.0000652	
1960	0.0819	0.0000144	
1961	0.8102	0.0001427	
1962	0.1524	0.0000268	
1963	0.1229	0.0000216	
1964	0.3371	0.0000594	
1965	0.2946	0.0000519	
1966	0.2227	0.0000392	
1967	0.4221	0.0000744	

San Simon River near Solomon, AZ drainage area 5677 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1968	0.1584	0.0000279	
1969	0.1161	0.0000205	
1970	0.0323	0.0000057	
Total	10.8762	0.0019145	3671.3
Average	0.3107	0.0000547	159.6

Creighton Reservoir, San Simon Wash Basin, AZ drainage area 275 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1956	0.0139	0.0000505	0
1957	0.1235	0.0004491	582.0
1958	0.0783	0.0002847	252.0
Total	0.2157	0.0007843	834.0
Average	0.0719	0.0002614	278.0

H-X Reservoir, San Simon Wash Basin, AZ drainage area 106 km^2

Year	Mean runoff m^3/s	Unit runoff $m^3/s/km^2$	Sediment discharge t/km^2
1956	0.0218	0.0002057	0
1957	0.0778	0.0007340	934.5
1958	0.5830	0.0055000	231.0
Total	0.6826	0.0064400	1165.5
Average	0.2275	0.0021466	388.5

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