# Rainfall simulation experiments in the Southwestern USA using the Walnut Gulch Rainfall Simulator.

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## Abstract

The dataset contains hydrological, erosion, vegetation, ground cover, and other supplementary information from 272 rainfall simulation experiments conducted on 23 semi-arid rangeland locations in Arizona and Nevada between 2002 and 2013. On 30% of the plots simulations were conducted up to five times during the decade of study. The rainfall was generated using the Walnut Gulch Rainfall Simulator on 2 m by 6 m plots. Simulation sites included brush and grassland areas with various degree of disturbance by grazing, wildfire, or brush removal. This dataset advances our understanding of basic hydrological and biological processes that drive soil erosion on arid rangelands. It can be used to estimate~~quantify~~ runoff, infiltration, and erosion rates on a variety of ecological sites in the Southwestern USA. Inclusion of wildfire and brush treatment locations combined with long term observations makes it important for studying vegetation recovery, ecological transitions, and effect of management. It is also a valuable resource for erosion model parameterization and validation.

The data set available from the National Agricultural Library at https://data.nal.usda.gov/search/type/dataset (DOI: 10.15482/USDA.ADC/1358583).

Key words: soil erosion, rainfall simulator, runoff, infiltration, ground cover, rangeland

## 1. Introduction

Soil erosion negatively impacts rangelands by impairing their ability to produce biomass (Stavi et al., 2009; Yisehak et al., 2013). The extent of this influence in comparison with other environmental and anthropogenic factors is poorly understood. Preservation and sustainable management of semi-arid ecosystems requires good knowledge of the physical processes involved in soil erosion and their interaction with plant communities. The experimental data needed to generate this knowledge is limited in time and space and often lacks ecological context in which it was gathered. Further, such data are difficult and costly~~or often impossible~~ to acquire by instrumenting natural hydrological systems (Nichols, 2006).

Artificial rainfall experiments on small plots provide a relatively quick and economical way to obtain necessary erosion information in a controlled and replicable setting (Lascelles et al., 2000; Parsons and Lascelles, 2000; Yakubu and Yusop, 2017). Field experiments under simulated rainfall have been conducted in the US since 1930s using stationary sprinkler systems (Meyer and McCune, 1958). Later simulators utilized a rotating boom design and V-jet nozzles (Swanson, 1965), which enhanced uniformity and allowed easier control of rainfall intensity. Further advancement came with the development of a portable Walnut Gulch Rainfall Simulator (WGRS) that featured improved spatial distribution of rainfall over a wider plot area, with rainfall energy and drop sizes similar to those of natural events (Paige et al., 2004).

The presented rainfall simulation data were collected by the Southwest Watershed Research Center (SWRC) over the period of 12 years (2002-2013) using WGRS. The set encompasses 272 simulation experiments conducted on 23 rangeland sites located in ~~four Major Land Resource Areas (MLRA), namely 28B, 38-3, 41-1, and 41-3. A total of 272 simulation experiments were conducted on 154 runoff plots.~~ grassland, shrub land, juniper, and oak savanna communities, many of which were affected by ~~Among these plots 53 were permanent, established to monitor long term ecological site transitions triggered by~~ wildfire, grazing, or brush and tree removal. ~~Plots at any given site were replicated four times in most cases.~~ The dataset contains hydrological (runoff rate and flow velocity) and erosion (sediment concentration and rate) measurements obtained over a wide range (60 mm h$^{-1}$ to 180 mm h$^{-1}$) of rainfall intensities. Ground cover (vegetation, basal, litter, rock, soil) and other supporting information are also provided~~ for every plot~~. The dataset is supplemented with ~~orthogonal ground cover~~ photographs of individual plots and landscapes~~taken prior to every simulation~~. The compiled and organized dataset will facilitate better dissemination of information among researchers enabling further insights into soil erosion processes. It will compliment a similar and ongoing efforts by SWRC to document long term watershed scale processes on arid rangelands (Nichols et al., 2008; Stone et al., 2008).

Our objectives are to provide information on: a) basic erosion processes and interactions between rainfall, runoff, infiltration, surface cover, and their spatial variability; b) erosion rates on different ecological sites; c) the impacts of grazing, brush treatment, wildfires, and ecological transitions on erosion; d) parameters for hydrological and erosion models and their validation.

## 2. Experimental area

Twenty three rainfall simulation sites were established throughout Arizona and Nevada rangelands (Table 1, Appendix B). In Arizona the climate is defined by the North American Monsoon (Adams and Comrie, 1997). Most of precipitation is delivered by short-duration, high intensity convective storms that occur July through September. May and June are the driest months of the year.

Six sites were located at Walnut Gulch Experimental Watershed (WGEW) in the upper San Pedro River basin in southeastern Arizona in CRA 41.AZ3 (Chihuahuan-Sonoran Semidesert Grasslands). Mean annual temperature in the area is 17.7° C. The LH and CR sites are located on Limy Upland (R041XC309AZ) that dominate the western portion of the WGEW. The representative soil series there are Luckyhill (Coarse-loamy, mixed, superactive, thermic Ustic Haplocalcids) and McNeal (Fine-loamy, mixed, superactive, thermic Ustic Calciargids) very gravely sandy loam (NRCS, 2003). The soil consists of approximately 39% gravel, 32% sand, 16% silt, and 13% clay. Limy Uplands have enough precipitation (290 mm $y^{-1}$) to support grass communities, however the soils (coarse textured and high in carbonates) favor drought tolerant shrubs, such as creosote (*Larrea tridentata* (DC.) Coville) and whitethorn (*Acacia constricta* Benth.). Grasses in this environment account for no more than 30% of biomass production, even less if the area is grazed. Brush control measures on Limy Uplands have low chance of long-term success. Kendall sites (K2, K3) are located on Loamy Upland (R041XC313AZ). The area receives an average of 345 mm of precipitation a year. The soils there are a complex of Stronghold (Coarse-loamy, mixed, thermic Ustollic Calciorthids), Elgin (Fine, mixed, thermic, Ustollic Paleargids), and McAllister (Fine-loamy, mixed, thermic, Ustollic Haplargids) (NRCS, 2003). Stronghold, a dominant soil, contains 67% sand, 16% silt, and 17% clay, with 79% coarse fragments (>2 mm). The organic carbon content of the soil surface (0–2.5 cm) is 1.1%. Desert bunchgrasses, such as black grama (*Bouteloua eriopoda* Torr.), sideoats grama (*B. curtipendula* Torr.), three-awn (*Aristida* sp.), and cane beardgrass (*Bothriochloa barbinodis* (Lag.) Herter) and forbs dominate the area. Some shrubs and succulents are also present. The site has been affected by a recent Lehmann lovegrass (*Eragrostis lehmanniana* Nees) invasion (Moran et al., 2009; Polyakov et al., 2010).

Six rainfall sites located on the historic Empire Ranch northeast of Sonoita, Arizona are also in CRA41.AZ3 and all are Loamy Uplands. Empire Ranch has been heavily grazed in the past, although the timing and extent of grazing is poorly documented. The annual precipitation at these locations ranges between 300 and 400 mm $y^{-1}$ The soils are gravelly loams and belong to the White House (fine, mixed, thermic, Ustollic Haplargids) soil series (NRCS, 2003). They were formed on alluvial fans and are characterized by a shallow A horizon underlain by deep argillic and calcic horizons. Sites ER1, ER2, and ER5 have historic climax plant community (HCPC) dominated by beardgrass (*Bothriochloa* spp.), grama (*Bouteloua* spp.), lovegrass (*Eragrostis* spp.), three-awn (*Aristida* spp.), and native forbs. ER3, ER4S, and ER4G have Mesquite-native plant community. All Empire Ranch sites were being grazed at the time of the experiments, except ER5 which has been an exclosure since the mid 1980s. The ER2 site had a wildfire in 2000 and had heavy grazing until the mid 2000s. ER3 site burned in 2005 prior to rainfall simulation that year. The ER4S has established mesquites on the plots and the mesquites on ER4G had been mechanically removed in 2006 a month after rainfall simulation. By 2010, the mesquite had re-sprouted and was approximately 2 m tall. ER4S and ER4G are located in close proximity to each other and share the same hydro-ecological characteristics.

San Rafael Valley and Audubon Ranch south of Sonoita, Arizona contained six simulation locations. SA and Ab in San Rafael Valley are located in CRA 41.AZ1 (Mexican Oak-Pine Forest and Oak Savannah) at 1550-1600 m elevation in 400-500 mm precipitation zone. Vegetation there includes Emory oak (*Quercus emoryi* Torr.), Mexican blue oak (*Q. oblongifolia* Torr.), Arizona white oak (*Q. arizonica* Sarg.), and grama species (*Bouteloua* spp.).

The ecological sites in this area are Loamy Uplands (PC, Wi, Ab, and SA), Loamy Slope (EM) and Clay Loam Uplands (Ta). San Rafael Valley is dominated by the White House soil series. The soil on EM is Terrarossa (Fine, mixed, superactive, thermic Aridic Paleustalfs), and on PC is Blacktail (Fine, mixed, superactive, thermic Calcidic Argiustolls). PC, EM, Wi and Ta sites are grasslands dominated by black grama (*Bouteloua eriopoda* Torr.), plains lovegrass (*Eragrostis intermedia* Hitchc.), and cane bluestem (*Bothriochloa barbinodis* (Lag.) Herter) with inclusion of native forbs. All of the sites experienced recent wildfires: EM, and PC in 2002, Ab in 2003, Ta in 2004, SA in 2005, and Wi in 2006. On all San Rafael Valley sites a set of natural (non-burned) plots were established next to the burn sites as a control. Grasslands have been under USFS grazing management plan during time of the experiments.

Three experimental sites (Yg1, Yg2, and Yg3) were located 9 km north of Young, Arizona in Major Land Resource Area (MLRA) 38 (Mogollon Transition Area) on Clay Loam Upland (R038XC303AZ) (USDA, 2006). The average annual precipitation in the area is 580 mm and the mean annual temperature is 11° C. Snow falls occasionally in winter. The soil is Terrarosa clayloam (Fine, mixed, superactive, thermic Aridic Paleustalfs). It is deep and well drained with > 1% organic matter, has a well developed argillic horizon and can be easily compacted by livestock when moist.  The depth of soil freezing in the winter is 10-15 cm. Yg1 and Yg2 sites are in HCPS (Historic Climax Plant Community) state dominated by grama species (*Bouteloua sp.*) (canopy cover of 40 to 60%) and cool season grasses. Mean annual production of above ground biomass estimated at 1600 kg/ha and effective rooting depth of perennial grasses is 70 cm. Possible STM transition (with disturbance, invasion or alteration of fire regimes) is to juniper woodland. Wildfires in the area occur every 10 to 15 years. Yg3 was in alligator juniper woodland state. Juniper was mechanically removed on the site a year prior to 2012 rainfall simulation.

Two sites (PCE, PCW) were located in Nevada, 100 km east of Fallon in MLRA 28B (Central Nevada Basin and Range) on Loamy Slopes (028BY113NV). The climate associated with this site is semi-arid, characterized by cold, moist winters and warm, dry summers with large temperature variations. The driest period is from mid-summer to mid-autumn. Average annual precipitation is 400 mm. Mean annual air temperature is 6° C and freeze-free period averages 125 days. The soil on the site is Tierney series (Loamy-skeletal, mixed, superactive, frigid Cumulic Haploxerolls). It is formed in alluvium derived from mixed parent material, very deep, well drained and has very low available water capacity. Clay content averages 12% and rock fragments are 35% by volume. The dominant vegetation on the site is bluegrass (*Poa annua* L.), mountain big sagebrush (*Artemisia tridentata* Nutt.), needle and thread (*Hesperostipa comata* (Trin. & Rupr.) Barkworth), rubber rabbitbrush (*Ericameria nauseosa* (Pall. ex Pursh) G.L. Nesom & Baird), sedge (*Cyperaceae* spp.), and western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve). Fire return interval varies from 15 to 25 years. Plants are readily killed in all seasons, even by light severity fires. Overgrazing and decline of ecological conditions leads to an increase in big sagebrush and decline in understory plants.

## 3. Instrumentation

### *3.1. Water application*

Rainfall was generated by WGRS, a portable, computer-controlled, variable intensity simulator (Paige et al., 2004). The WGRS can deliver rainfall rates ranging between 13 and 178 mm h$^{-1}$ with variability coefficient of 11% across 2 by 6.1 m area. Estimated kinetic energy of simulated rainfall was 204 kJ $ha^{-1}$ $mm^{-1}$ and drop size ranged from 0.288 to 7.2 mm. The simulator is equipped with a single oscillating boom with four V-jet nozzles with overlapping spray pattern and 50° sweep. The operating height of the nozzles is 2.4 m above ground at 55 kPa water pressure. The oscillations are controlled by a high torque stepper motor that varies the speed of the nozzles, slower at the ends of the oscillation and faster in the middle when the nozzles are pointed directly down. This approach improves uniformity of the water application across the plot. The spray time and sequence are controlled by three-way solenoids. A PC and a controller are used to setup various rainfall programs. Detailed description and design of the simulator is available in Paige et al. (2004). Prior to each field season the simulator was calibrated over a range of intensities using a set of 56 rain gages arranged on the plot in rectangular grid. During the experiments windbreaks were placed around the simulator to minimize the effect of wind on rain distribution. The general view of the simulator with windbreaks, runoff flume, and control equipment is shown on ~~(~~Figure~~.~~ 1~~)~~.

During 93 simulations run-on flow was applied at the top edge of the plot using a perforated pipe placed horizontally over a narrow strip of cloth directly on the soil surface. This arrangement ensured uniform initial sheet flow and prevented localized scour. The purpose of run-on water application was to simulate hydrological processes that occur on longer slopes (>6 m) where the upper portion of the slope contributes runoff onto the lower portion. In a limited number of experiments run-on flow rate was unknown. In these cases it was labeled as “rate1”, “rate2” etc. in the data file.

### *3.2. Runoff*

Runoff rate from the plot was measured using a V-shaped supercritical flume positioned at 4% slope and equipped with an electronic depth gage. Flow depth was recorded manually and converted to flow rate using the following depth to discharge relationship:

$$Q = ah^b \qquad (1)$$

where Q is discharge (L $s^{-1}$), h is flow depth in the flume (mm), a and b are calibration coefficients. The flume was calibrated before every field season.

### *3.3. Flow velocity*

Overland flow velocities on the plots were measured using electrolyte and fluorescent dye solution starting in 2006. Two liters of the solution were uniformly applied on the surface using a perforated PVC pipe placed across the plot 3.3 m from the outlet. Dye moving from the application point to the outlet was timed with a stopwatch. Electrolyte transport in the flow was measured by resistivity sensors imbedded in edge of the outlet flume at the end of the plot. The data was collected at 0.37 s intervals with real time graphical output using LoggerNet software and CR10X data logger by Campbell Scientific. Maximum flow velocity (Vm, m $s^{-1}$) was defined as velocity of the leading edge of the solution and was determined from ~~beginning of the breakthrough curve (Fig. 2) and verified by visual observation of~~ dye front. Mean flow velocity (Va, m $s^{-1}$) was calculated using mean travel time obtained from the salt concentration breakthrough curve (Fig. 2) and the following equation:

$$T_a = \sum_{i=t_s}^{t_e} c_i t_i \Big/ \sum_{i=t_s}^{t_e} c_i \qquad (2)$$

where $t_s$ is curve start time (s), $t_e$ is curve end time or return to baseline (s), $t_i$ is instantaneous time (s), and $c_i$ is normalized conductivity.

### *3.4. Erosion.*

Sediment concentrations from the plots were determined from 1 liter runoff samples collected during each run. Sampling interval time was variable and aimed to represent rising and falling limbs of the hydrograph, any changes in runoff rate, and steady state conditions (a minimum of 3 samples). This resulted in approximately 30 to 50 samples per simulation. A coagulant solution was added to the samples to flocculate and settle the sediments. After the settling, the excess water was decanted and the sediments were dried at $105^0$ C. Wet and dry samples were weighed and sediment concentration in the runoff samples calculated gravimetrically. Soil losses were determined from the combination of sediment concentration and discharge rates.

### *3.5. Vegetation and surface cover.*

Shortly before simulations plot surface and vegetative cover was measured at 400 points on a 15 x 20 cm grid using a laser and line-point intercept procedure (Herrick et al., 2005). Vegetative cover was classified as forbs, grass, and shrub. Surface cover was characterized as rock, litter, plant basal area, and bare soil. These 4 metrics were further classified as protected (located under plant canopy) and unprotected (not covered by the canopy).

In addition, plant canopy and basal gaps were measured on the plots over three lengthwise and six crosswise transects. These were reported as the sum and the average of all inter canopy and inter basal spaces greater than 10 cm along the transects.

## **4. Experimental procedure**

Four to eight 6.1 by 2 m replicated rainfall simulation plots were established on each site (Mayerhofer et al., 2017). The plots were bound by sheet metal borders hammered into the ground on three sides. On the down slope side a collection trough was installed to channel runoff into the measuring flume. If a site was revisited, repeat simulations were always conducted on the same long term plots. In these cases the lateral borders remained installed in the field, while top the border and runoff flume were removed to avoid obstructing natural runoff during interim period.

The plots were classified as “burn”~~-~~ or “natural” (labeled as “B” or “N” respectively in Appendix B). The burn plots were established on six sites affected by wildfires that occurred between 2000 and 2006 ~~(Table X)~~ . These plots were in various stages of recovery during the experiments. The natural plots had no recent documented wildfires. With the exception of Audubon Research Ranch burn plots were paired with natural control plots located on the same site in close proximity. On 53 plots (13 sites) rainfall simulations were repeated up to 5 times in the following years (2002 through 2013) in order to monitor post brush treatment, burn recovery, or ecological site transition.

The experimental procedure was as follows. First, the plot was subjected to 45 min long, 65 mm $h^{-1}$ intensity simulated rainfall (dry run) intended to create initial saturated condition that could be replicated across all sites. This was followed by a 45 minute pause and a second simulation with varying intensity (wet run) (Fig. 3). During wet runs two modes of water application were used as previously described: rainfall and run-on. Rainfall only wet runs accounted for 79% of simulations, while the rest were run-on flow only, or a combination of rainfall and run-on flow. Table 2 shows an excerpt from one of 272 simulation data sheets. The first seven columns are site attributes and the rest are time series of data recorded during the run. N/A indicates not measured or missing. Run time (min) of each experiment begins at commencement of water application and ends at cessation of runoff.

Rainfall wet runs typically consisted of series of application rates (65, 100, 125, 150, and 180 mm $h^{-1}$) that were increased after runoff had reached steady state for at least five minutes. Runoff samples were collected on the rising and falling limb of the hydrograph and during each steady state (a minimum of 3 samples). Overland flow velocities were measured during each steady state as previously described. Run-on wet runs followed the same procedure as rainfall runs, except water application rates varied between 100 and 300 mm $h^{-1}$.

In approximately 20% of simulation experiments wet run was followed by another simulation (wet2 run) after a 45 min pause. Wet2 runs were similar to wet runs and also consisted of series of varying intensity rainfalls and/or run-on input.

## 5. Data availability

The data set available from the National Agricultural Library at website https://data.nal.usda.gov/search/type/dataset (DOI: 10.15482/USDA.ADC/1358583). It includes short description and methods, data dictionary, geographic information, hydrological, erosion, and vegetation data files, and a set of sites and plot images.

## 6. Conclusion

Soil erosion researchers study complex system with large number of temporally variable inputs, interactions, feedbacks, and stochastic relationships. Many variables are difficult to measure accurately. Hence, it is critical to assemble comprehensive and long term datasets to enable robust statistical analysis, facilitate comparisons and detect long term trends. There is also a need to standardize rainfall simulators and experimental protocols (Kibet et al., 2014) and provide for better dissemination of collected information among researchers (Parsons and Lascelles, 2000).

This paper presents the results of 272 rainfall simulation experiments on small plots in semi-arid rangelands of southwestern USA. The experiments spanning 12 years were conducted in Arizona and Nevada in four MLRAs (28B, 38-1, 41-1, 41-3) and represented four ecological sites (Clay loam upland, Limy upland, Loamy slope, Loamy upland). These sites are characterized by coarse gravely soils and annual precipitation of 250 to 500 mm.

The simulations were conducted under a wide range of rainfall intensities (60 mm $h^{-1}$ to 180 mm $h^{-1}$) on plots with a variety of slopes (4% to 40%), ground cover (22% to 99%), and foliar cover (0-85%). Many of the locations have been affected by grazing, wildfire, or brush treatment and were in various stages of recovery or ecological transition during the experiments. Repeat multi-year simulations and detailed vegetation and land management records place the results in a broader ecological context, rare for this type of studies.

Runoff and erosion rates on plots were affected by high heterogeneity and complex spatial structure of rangeland sites. Gravelly soils often develop a surface rock layer with increased roughness resulting in complex hydrological interactions. Hence, variability between replicated plots was greater than typically observed on cultivated fields. The variation in sediment yield during runs was also significant, suggesting that 3 runoff samples may not be enough to accurately characterize a steady state sediment yield at a given rainfall rate.  In a small number of simulations run-on flow rates were unknown as previously described. Care must be taken when scaling the results to a hill slope or watershed size. On the plot size areas surface roughness, vegetation pattern, sheet to rill flow transition are critical factors, while lithology, topography, and channel network need to be considered at greater spatial magnitude (Kirkby et al., 1996). Transmission losses of sediment and runoff at slope (Parsons et al., 2006) and watershed (Lane et al., 1997) scales have been observed. Although the simulator was shielded from wind while in operation some wind interference should not be discounted.

The scope of this data set combined with state of the art rainfall simulation equipment makes it particularly valuable to advance our understanding of basic erosion and transport processes specific to arid rangelands. Orthogonal photographs of the plots provide basis for cover structure and connectivity analysis. The data can be used to evaluate and compare management practices, and study ecological states, transitions and thresholds. It can also support erosion model development and validation.

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## Figure captions

Figure 1. Walnut Gulch Rainfall Simulator.
Figure 2. Breakthrough curve of electrolyte solution in runoff at 150 mm $h^{-1}$ rainfall intensity.
Figure 3. Typical hydrograph of a rainfall simulation run.

## Tables

Table 1. Summary of rainfall simulation sites.

| ~~Location~~ | ~~Site~~ | ~~Coordinates~~ | | ~~MLRA~~ | ~~Vegetation~~ | ~~Soil texture~~ | ~~Plot~~ | ~~Average slope,~~ | ~~Simulation years~~ |
|---|---|---|---|---|---|---|---|---|---|
| | ~~ID~~ | ~~Latitude~~ | ~~Longitude~~ | | ~~type~~ | | ~~N~~ | ~~%~~ | |
| ~~Audubon Ranch~~ | ~~EM~~ | ~~31.589794~~ | ~~-110.48768~~ | ~~41-3~~ | ~~perennial grass~~ | ~~sandy loam~~ | ~~4~~ | ~~13.0~~ | ~~2002, 2003, 2004~~ |
| | ~~PC~~ | ~~31.585556~~ | ~~-110.52750~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~8~~ | ~~8.0~~ | ~~2002, 2003, 2004. 2006~~ |
| ~~Empire Ranch~~ | ~~ER1~~ | ~~31.708600~~ | ~~-110.58840~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~4~~ | ~~12.9~~ | ~~2003~~ |
| | ~~ER2~~ | ~~31.708600~~ | ~~-110.58840~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~8~~ | ~~12.9~~ | ~~2003, 2007, 2010, 2013~~ |
| | ~~ER3~~ | ~~31.764270~~ | ~~-110.55947~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~12~~ | ~~13.3~~ | ~~2005, 2006, 2009, 2013~~ |
| | ~~ER4G~~ | ~~31.795705~~ | ~~-110.61760~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~8~~ | ~~4.7~~ | ~~2006, 2010, 2013~~ |
| | ~~ER4S~~ | ~~31.795644~~ | ~~-110.61870~~ | ~~41-3~~ | ~~shrub~~ | ~~gravely loam~~ | ~~4~~ | ~~4.3~~ | ~~2006, 2007, 2010, 2013~~ |
| | ~~ER5~~ | ~~31.756388~~ | ~~-110.67916~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~4~~ | ~~6.3~~ | ~~2010~~ |
| ~~Porter Canyon~~ | ~~PCE~~ | ~~39.463703~~ | ~~-117.62154~~ | ~~28B~~ | ~~juniper~~ | ~~very gravely loam~~ | ~~6~~ | ~~35.8~~ | ~~2009~~ |
| | ~~PCW~~ | ~~39.463841~~ | ~~-117.62253~~ | ~~28B~~ | ~~juniper~~ | ~~cobbly sandy loam~~ | ~~4~~ | ~~23.5~~ | ~~2009~~ |
| ~~San Rafael Valley~~ | ~~Ab~~ | ~~31.441152~~ | ~~-110.52191~~ | ~~41-1~~ | ~~oak savanna~~ | ~~gravely loam~~ | ~~8~~ | ~~10.3~~ | ~~2003, 2004, 2005, 2007~~ |
| | ~~SA~~ | ~~31.390278~~ | ~~-110.64945~~ | ~~41-1~~ | ~~oak savanna~~ | ~~gravely loam~~ | ~~8~~ | ~~16.1~~ | ~~2005, 2006, 2009~~ |
| | ~~Ta~~ | ~~31.413741~~ | ~~-110.63900~~ | ~~41-3~~ | ~~perennial grass~~ | ~~very gravely loam~~ | ~~8~~ | ~~25.4~~ | ~~2004, 2005, 2007~~ |
| | ~~Wi~~ | ~~31.452168~~ | ~~-110.63390~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely loam~~ | ~~8~~ | ~~8.4~~ | ~~2006, 2007, 2010~~ |
| ~~WGEW~~ | ~~K2~~ | ~~31.736116~~ | ~~-109.94335~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely fine sandy loam~~ | ~~8~~ | ~~10.8~~ | ~~2005, 2007, 2008, 2010, 2013~~ |
| | ~~K3~~ | ~~31.736116~~ | ~~-109.94335~~ | ~~41-3~~ | ~~perennial grass~~ | ~~gravely fine sandy loam~~ | ~~8~~ | ~~9.7~~ | ~~2008~~ |
| | ~~CR~~ | ~~31.684345~~ | ~~-109.99314~~ | ~~41-3~~ | ~~shrub~~ | ~~gravely sandy loam~~ | ~~6~~ | ~~14.7~~ | ~~2009~~ |
| | ~~LH1~~ | ~~31.740670~~ | ~~-110.05330~~ | ~~41-3~~ | ~~shrub~~ | ~~gravely sandy loam~~ | ~~6~~ | ~~15.8~~ | ~~2003, 2007~~ |
| | ~~LH2~~ | ~~31.740670~~ | ~~-110.05330~~ | ~~41-3~~ | ~~shrub~~ | ~~gravely sandy loam~~ | ~~8~~ | ~~7.8~~ | ~~2008~~ |
| | ~~LH3~~ | ~~31.741970~~ | ~~-110.05440~~ | ~~41-3~~ | ~~shrub~~ | ~~gravely sandy loam~~ | ~~4~~ | ~~8.4~~ | ~~2004~~ |
| ~~Young, AZ~~ | ~~Yg1~~ | ~~34.178203~~ | ~~-110.98083~~ | ~~38-1~~ | ~~perennial grass~~ | ~~clay loam~~ | ~~8~~ | ~~12.7~~ | ~~2011~~ |
| | ~~Yg2~~ | ~~34.178891~~ | ~~-110.98081~~ | ~~38-1~~ | ~~perennial grass~~ | ~~clay loam~~ | ~~8~~ | ~~8.8~~ | ~~2011, 2012~~ |
| | ~~Yg3~~ | ~~34.185290~~ | ~~110.92450~~ | ~~38-1~~ | ~~treated juniper~~ | ~~clay loam~~ | ~~8~~ | ~~5.2~~ | ~~2012~~ |

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| Location | Site ID | MLRA | Ecological site | Precipitation mm | Vegetation type | Soil texture | Plot N | Slope % | Simulation years |
|---|---|---|---|---|---|---|---|---|---|
| Audubon Ranch | EM | 41-3 | Loamy Slope | 300-400 | perennial grass | sandy loam | 4 | 13.0 | 2002, 2003, 2004 |
| | PC | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely loam | 8 | 8.0 | 2002, 2003, 2004. 2006 |
| Empire Ranch | ER1 | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely loam | 4 | 12.9 | 2003 |
| | ER2 | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely loam | 8 | 12.9 | 2003, 2007, 2010, 2013 |
| | ER3 | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely loam | 12 | 13.3 | 2005, 2006, 2009, 2013 |
| | ER4G | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely loam | 8 | 4.7 | 2006, 2010, 2013 |
| | ER4S | 41-3 | Loamy Upland | 300-400 | shrub | gravely loam | 4 | 4.3 | 2006, 2007, 2010, 2013 |
| | ER5 | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely loam | 4 | 6.3 | 2010 |

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| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Porter | PCE | 28B | Loamy Slope | 400-500 | juniper | very gravely loam | 6 | 35.8 | 2009 |
| Canyon | PCW | 28B | Loamy Slope | 400-500 | juniper | cobbly sandy loam | 4 | 23.5 | 2009 |
| San | Ab | 41-1 | Loamy Upland | 400-500 | oak savanna | gravely loam | 8 | 10.3 | 2003, 2004, 2005, 2007 |
| Rafael | SA | 41-1 | Loamy Upland | 400-500 | oak savanna | gravely loam | 8 | 16.1 | 2005, 2006, 2009 |
| Valley | Ta | 41-3 | Clay Loam Upland | 300-400 | perennial grass | very gravely loam | 8 | 25.4 | 2004, 2005, 2007 |
| | Wi | 41-3 | Loamy Upland | 400-500 | perennial grass | gravely loam | 8 | 8.4 | 2006, 2007, 2010 |
| WGEW | K2 | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely fine sandy loam | 8 | 10.8 | 2005, 2007, 2008, 2010, 2013 |
| | K3 | 41-3 | Loamy Upland | 300-400 | perennial grass | gravely fine sandy loam | 8 | 9.7 | 2008 |
| | CR | 41-3 | Limy Upland | 300-400 | shrub | gravely sandy loam | 6 | 14.7 | 2009 |
| | LH1 | 41-3 | Limy Upland | 300-400 | shrub | gravely sandy loam | 6 | 15.8 | 2003, 2007 |
| | LH2 | 41-3 | Limy Upland | 300-400 | shrub | gravely sandy loam | 8 | 7.8 | 2008 |
| | LH3 | 41-3 | Limy Upland | 300-400 | shrub | gravely sandy loam | 4 | 8.4 | 2004 |
| Young | Yg1 | 38-1 | Clay Loam Upland | 500-600 | perennial grass | clay loam | 8 | 12.7 | 2011 |
| | Yg2 | 38-1 | Clay Loam Upland | 500-600 | perennial grass | clay loam | 8 | 8.8 | 2011, 2012 |
| | Yg3 | 38-1 | Clay Loam Upland | 500-600 | treated juniper | clay loam | 8 | 5.2 | 2012 |

Table 2. An example of rainfall simulation data organization.

| Site ID | Plot condition | Plot # | Year | Month | Day | Run Type | Run Time | Precipitation | Run-on flow | Runoff Discharge | Sediment Concentration | Sediment Discharge | Flow velocity | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | surface | mean |
| | | | | | | | min | mm/h | mm/h | mm/h | % | g/s | m/s | m/s |
| ER2 | N | 1 | 2013 | 7 | 30 | DRY | 0 | 74~~3.66~~ | 0~~.00~~ | 0~~.00~~ | N/A | 0.00 | 0.00 | 0.00 |
| ER2 | N | 1 | 2013 | 7 | 30 | DRY | 6.33 | 74~~3.66~~ | 0~~.00~~ | 0~~.00~~ | N/A | 0.00 | 0.00 | 0.00 |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| ER2 | N | 1 | 2013 | 7 | 30 | DRY | 40 | 74~~3.66~~ | 0~~.00~~ | 9~~.44~~ | 0.28 | 0.09 | N/A | N/A |
| ER2 | N | 1 | 2013 | 7 | 30 | DRY | 45 | 0 | 0~~.00~~ | 9~~.44~~ | 0.16 | 0.05 | N/A | N/A |
| ER2 | N | 1 | 2013 | 7 | 30 | DRY | 45.67 | 0 | 0~~.00~~ | 4~~3.90~~ | 0.08 | 0.01 | N/A | N/A |
| ER2 | N | 1 | 2013 | 7 | 30 | DRY | 46.33 | 0 | 0~~.00~~ | 0~~.00~~ | N/A | 0.00 | N/A | N/A |
| ER2 | N | 1 | 2013 | 7 | 30 | WET | 0 | 74~~3.66~~ | 0~~.00~~ | 0~~.00~~ | N/A | N/A | N/A | N/A |
| ER2 | N | 1 | 2013 | 7 | 30 | WET | 4.58 | 77~~3.66~~ | 0~~.00~~ | 0~~.00~~ | N/A | N/A | N/A | N/A |
| ER2 | N | 1 | 2013 | 7 | 30 | WET | 46 | 153~~.42~~ | 0~~.00~~ | 109~~8.90~~ | 0.13 | 0.50 | N/A | N/A |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| ER2 | N | 1 | 2013 | 7 | 30 | WET | 48 | 153~~.42~~ | 0~~.00~~ | 109~~8.90~~ | 0.12 | 0.45 | 0.084 | 0.031 |
| ER2 | N | 1 | 2013 | 7 | 30 | WET | 50 | 153~~.42~~ | 0~~.00~~ | 109~~8.90~~ | 0.14 | 0.51 | N/A | N/A |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |

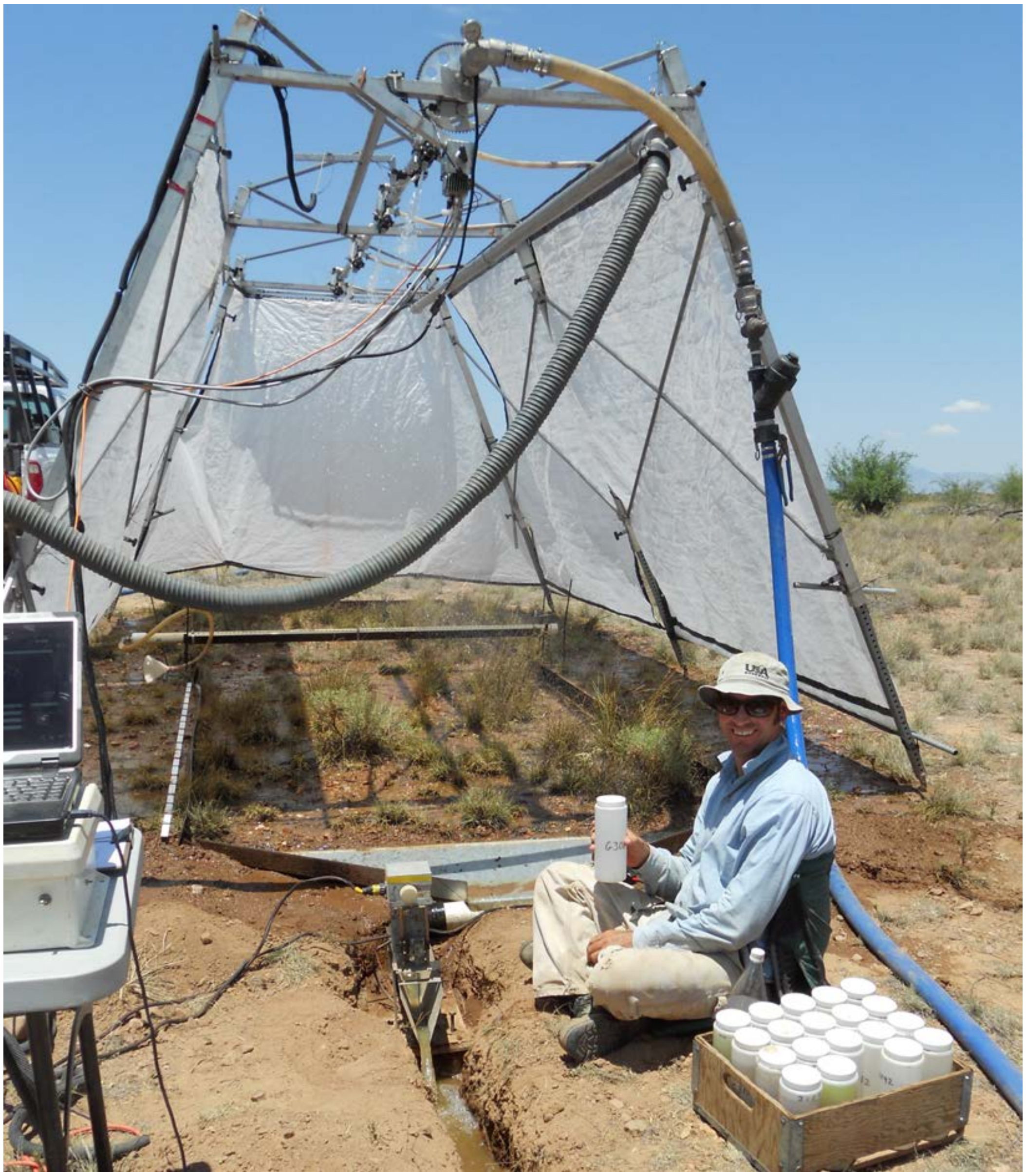

Figure 1. Walnut Gulch Rainfall Simulator.

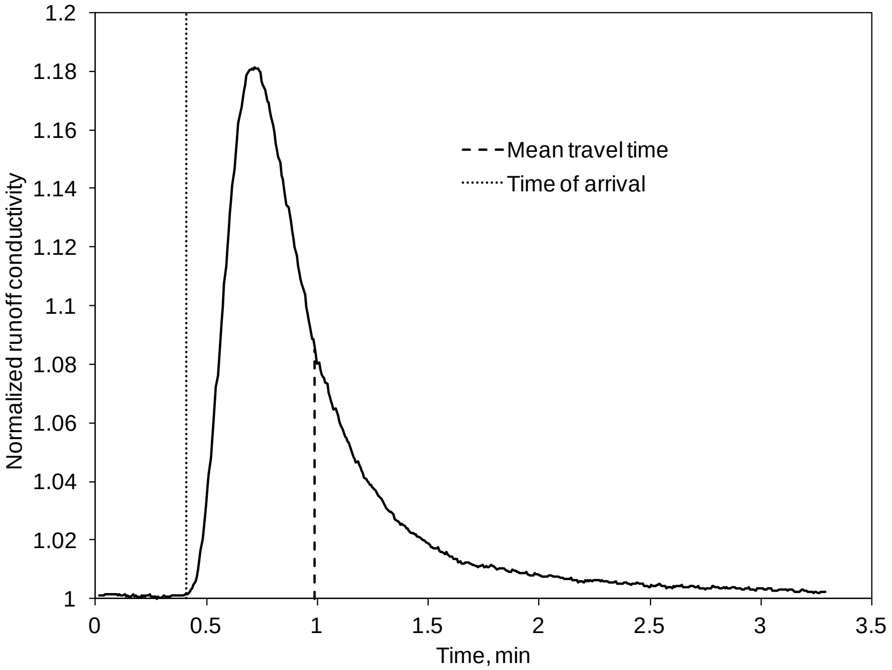

Figure 2. Electrolyte solution breakthrough curve in plot runoff at 150 mm $h^{-1}$ intensity.

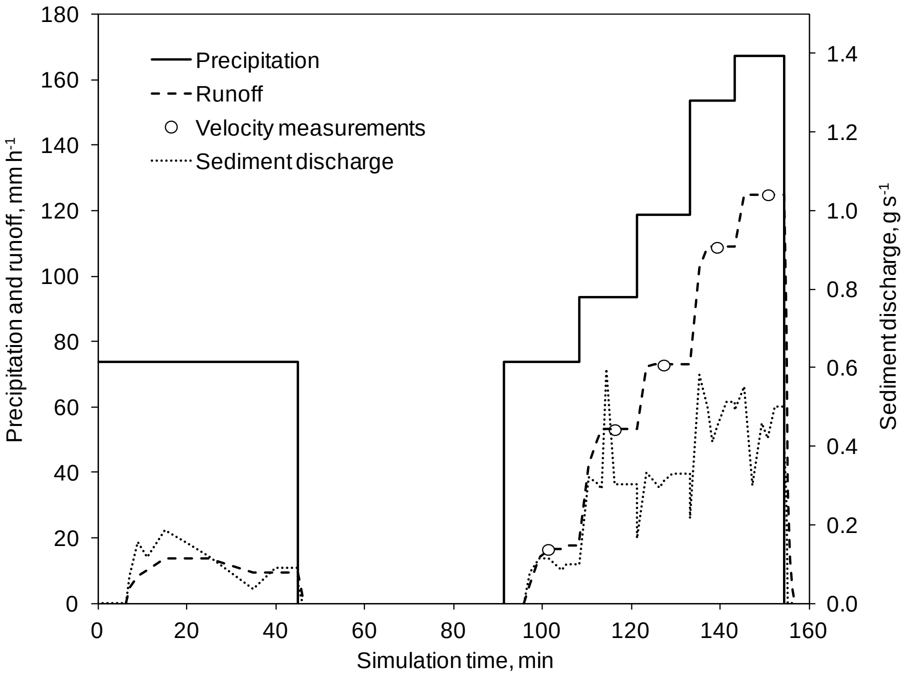

Figure 3. Typical hydrograph of a rainfall simulation run.