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Estimating the Effects of Conversion of Agricultural Land to Urban Land on Deep Percolation of Irrigation Water in the Grand Valley, Western Colorado

Scientific Investigations Report 2008–5086

U.S. Department of the Interior
U.S. Geological Survey

FRONT COVER

Left

Aerial photograph of Chipeta Pines Subdivision showing four study sites: two residential lawns, a pond, and a commons park. Photograph courtesy of Mesa County, Colorado GIS Department, 2001.

Right, Top to Bottom

Grand Valley Irrigation Study site bluegrass lawn being irrigated. Photograph by John Mayo, October 11, 2006.

Orchard grass field at Colorado State University Orchard Mesa Experiment Station, Grand Junction, Colorado. Photograph by John Mayo, May 23, 2006.

Paradise Hills Subdivision pond. Photograph by John Mayo, November 22, 2005.

BACK COVER

Top to Bottom

Colorado State University Extension Service investigator collecting runoff data at study site. Photograph by John Mayo, September 29, 2005.

U.S. Geological Survey investigators installing a broad-crested flume at Colorado State University Orchard Mesa Experiment Station field to measure runoff. Photograph by John Mayo, April 26, 2006.

U.S. Geological Survey investigator collecting sprinkler system flow data at a study site. Photograph by John Mayo, October 11, 2005.

U.S. Geological Survey investigators performing acoustic depth profile of Paradise Hills Subdivision pond. Photograph by Craig Muelot, October 18, 2005.

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Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Elevation, as used in this report, refers to distance above the vertical datum.

Additional Abbreviations Used in This Report

CSU Colorado State University
FC Field Capacity
NRCS National Resources Conservation Service
PWP Permanent Wilting Point
RAW Readily Available Water
REW Readily Evaporable Water
TAW Total Available Water
USDA U.S. Department of Agriculture
USGS U.S. Geological Survey

Estimating the Effects of Conversion of Agricultural Land to Urban Land on Deep Percolation of Irrigation Water in the Grand Valley, Western Colorado

By John W. Mayo

Abstract

The conversion of agricultural land to urban residential land is associated with rapid population growth in the Grand Valley of western Colorado. Information regarding the effects of this land-use conversion on deep percolation, irrigation-water application, and associated salt loading to the Colorado River is needed to support water-resource planning and conservation efforts. The Natural Resources Conservation Service (NRCS) assessed deep percolation and estimated salt loading derived from irrigated agricultural lands in the Grand Valley in a 1985 to 2002 monitoring and evaluation study (NRCS M&E). The U.S. Geological Survey (USGS), in cooperation with the Colorado River Salinity Control Forum and the Mesa Conservation District, quantified the current (2005–2006) deep percolation and irrigation-water application characteristics of 1/4-acre residential lots and 5-acre estates, urban parks, and urban orchard grass fields in the Grand Valley, and compared the results to NRCS M&E results from alfalfa-crop sites. In addition, pond seepage from three irrigation-water holding ponds was estimated. Salt loading was estimated for the urban study results and the NRCS M&E results by using standard salt-loading factors.

A daily soil-moisture balance calculation technique was used at all urban study irrigated sites. Deep percolation was defined as any water infiltrating below the top 12 inches of soil. Deep percolation occurred when the soil-moisture balance in the first 12 inches of soil exceeded the field capacity for the soil type at each site. Results were reported separately for urban study bluegrass-only sites and for all-vegetation type (bluegrass, native plants, and orchard grass) sites. Deep percolation and irrigation-water application also were estimated for a complete irrigation season at three subdivisions by using mean site data from each subdivision. It was estimated that for the three subdivisions, 37 percent of the developed acreage was irrigated (the balance being impermeable surfaces).

The mean season-total deep percolation for bluegrass-only sites at three residential subdivisions was 0.30 acre-foot per irrigated acre and 0.12 acre-foot per developed acre. The season-total deep percolation for all-vegetation type sites at the three subdivisions was 0.27 acre-foot per irrigated acre and 0.11 acre-foot per developed acre. Mean season-total deep percolation for alfalfa-crop sites in the NRCS M&E was 1.27 acre-feet per acre. For equivalent land areas, the conversion of land from agricultural to urban residential uses results in a potential deep percolation reduction of 91 percent for bluegrass-only sites and a potential reduction of 91 percent for all-vegetation type sites.

The mean season-total irrigation-water application for bluegrass-only sites in three residential subdivisions was 2.80 acre-feet per irrigated acre and 1.05 acre-feet per developed acre. The mean season-total irrigation-water application for all-vegetation type sites at the three subdivisions was 2.56 acre-feet per irrigated acre and 0.98 acre-foot per developed acre. Mean season-total irrigation-water application for alfalfa-crop sites in the NRCS M&E was 3.79 acre-feet per developed acre. For equivalent land areas, this represents a reduction of 72 percent in irrigation-water application for bluegrass-only sites compared with agricultural sites, and a reduction of 74 percent for all-vegetation type sites in subdivisions. On the basis of a limited data set, mean season-total irrigation-water holding pond seepage was estimated to be 11.94 acre-feet per surface acre.

Salt loading for urban bluegrass-only sites was estimated to be 0.25 ton per developed acre and for all-vegetation type sites was estimated to be 0.22 ton per developed acre. Mean salt loading for NRCS M&E alfalfa-crop sites was 2.60 tons per acre. As a ratio, compared with alfalfa-crop sites, this represents a salt-loading reduction factor of 10.4 for bluegrass-only sites and a reduction factor of 11.8 for all-vegetation type sites. Salt loading from ponds was estimated to be 24.48 tons per surface acre, a ratio increase over agricultural alfalfa-crop sites of 9.4.

Thus, the conversion of land from agricultural to residential urban subdivisions results in substantially lower irrigation-water application, lower deep percolation, and less salt loading per developed acre, with the exception of urban unlined ponds. Control of deep percolation from unlined ponds that are created to support residential irrigation could be an increasingly important factor to consider for minimizing irrigation-induced salt loading to the Colorado River.

Introduction

The Grand Valley, in Mesa County in western Colorado, contributes an average of 500,000 tons of salt annually to the Colorado River because of salt pickup from irrigation (Hedlund, 1994). Rapid population growth in the Grand Valley has led to the conversion of agricultural land to urban residential land. The Grand Valley is underlain primarily by the Mancos Shale of Cretaceous age (Butler and others, 1996). Deep percolation of irrigation water through soils derived from the Mancos Shale results in leaching of salt, which reaches the Colorado River. Some salt load is delivered to irrigated lands with the Colorado River-supplied irrigation water, but this initial salt load is accounted for in the salt-loading factor used in this study.

Changes in deep percolation characteristics have not previously been quantified for lands converted from agricultural to residential use. The Grand Valley and other salinity control units are experiencing substantial land-use changes due to the conversion of large agricultural areas to smaller land units. These smaller units represent both urban agriculture and residential landscaping. Salinity control programs need information about the long-term effects of previous irrigation system improvements on deep percolation characteristics and reduction of salt loading. Salinity control program managers need to understand how changing land use may affect expected salinity-reduction benefits that were estimated for changes in agricultural irrigation practices, but without consideration of subsequent conversion to urban land use.

The Natural Resources Conservation Service (NRCS) assessed deep percolation and estimated salt loading derived from irrigated agricultural lands in the Grand Valley in a 1985 to 2002 monitoring and evaluation study, hereinafter referred to as “NRCS M&E” (U.S. Department of Agriculture, 1986–2003). That assessment provided a baseline of deep percolation characteristics on agricultural land and has been used by NRCS to make management decisions related to salinity reduction projects.

The U.S. Geological Survey (USGS), in cooperation with the Colorado River Salinity Control Forum and the Mesa Conservation District, quantified the current (2005–2006) deep percolation and irrigation-water application characteristics of residential lots and estates, urban parks, and orchard grass fields in the Grand Valley, and compared the results to 1985–2002 NRCS M&E results from alfalfa-crop sites. Salt loading was estimated for the urban study results and the NRCS M&E results using standard salt-loading factors.

Purpose and Scope

This report presents estimates of the effects of conversion of agricultural land to urban land on deep percolation of irrigation water in the Grand Valley. Effects on the amounts of applied irrigation water and salt loading in the Colorado River are also discussed. The report details the methods used to collect data and the calculations used to estimate the effects of the land-use change. The urban study results are compared to the results of the 1985–2002 NRCS M&E. The study was divided into three parts: (1) calculation of irrigation-water application and deep percolation from turf grass, orchard grass, and native plants used in lawns and small pastures; (2) calculation of seepage from selected unlined irrigation holding ponds; and (3) comparison of irrigation-water application, deep percolation characteristics, and resulting salt loading in the Colorado River from the sites in this study to the alfalfa-crop sites in the NRCS M&E.

A daily soil-moisture balance calculation technique was used to calculate deep percolation at irrigated sites from the difference between inflow of irrigation water and effective precipitation and outflow of runoff and evapotranspiration. For this study, deep percolation for lawns and small pastures was defined as any water infiltrating below the top 12 inches of soil, which was assumed to be deeper than the turf-grass root zone. Daily deep percolation was calculated to have occurred when the daily soil-moisture balance exceeded the field capacity for the soil type at each site.

Additionally, pond seepage from three irrigation-water holding ponds was estimated. Holding ponds temporarily store water drawn from irrigation canals for whole subdivision irrigation systems and parks and are being installed throughout the Grand Valley as new subdivisions are developed. Deep percolation is normally considered to occur below the root zone of plants, while seepage is defined as loss from a body of water. For the purposes of salt-loading calculations, pond seepage in this report is treated as being functionally equivalent to deep percolation.

Finally, and most important, the irrigation-water application and deep percolation characteristics derived for the urban sites were compared to the results of the NRCS M&E. This comparison illustrates the effect of conversion from agricultural fields to urban lawns and pastures and provides for an estimate of changes in salt loading in the Colorado River from deep percolation of irrigation water.

Description of Study Area

The Grand Valley is in Mesa County in western Colorado, at the confluence of the Gunnison and Colorado Rivers (fig. 1). The valley is approximately 30 miles long and 5 miles wide. The principal city is Grand Junction, with a population of 45,000 in 2005, while the entire metropolitan area population in the Grand Valley was approximately 134,000 in 2006 (U.S. Census Bureau, 2007).

Historically, the Grand Valley has been a major fruit-growing region with a large number of orchards and small farms. Irrigation canals have provided ample and inexpensive water from the Colorado and Gunnison Rivers for Grand Valley agriculture since about 1900. The irrigation distribution infrastructure has been retained to provide irrigation water to urban developments as land-use conversion from agriculture to urban occurs. Irrigation water is typically available in the valley from mid-April through October each year.

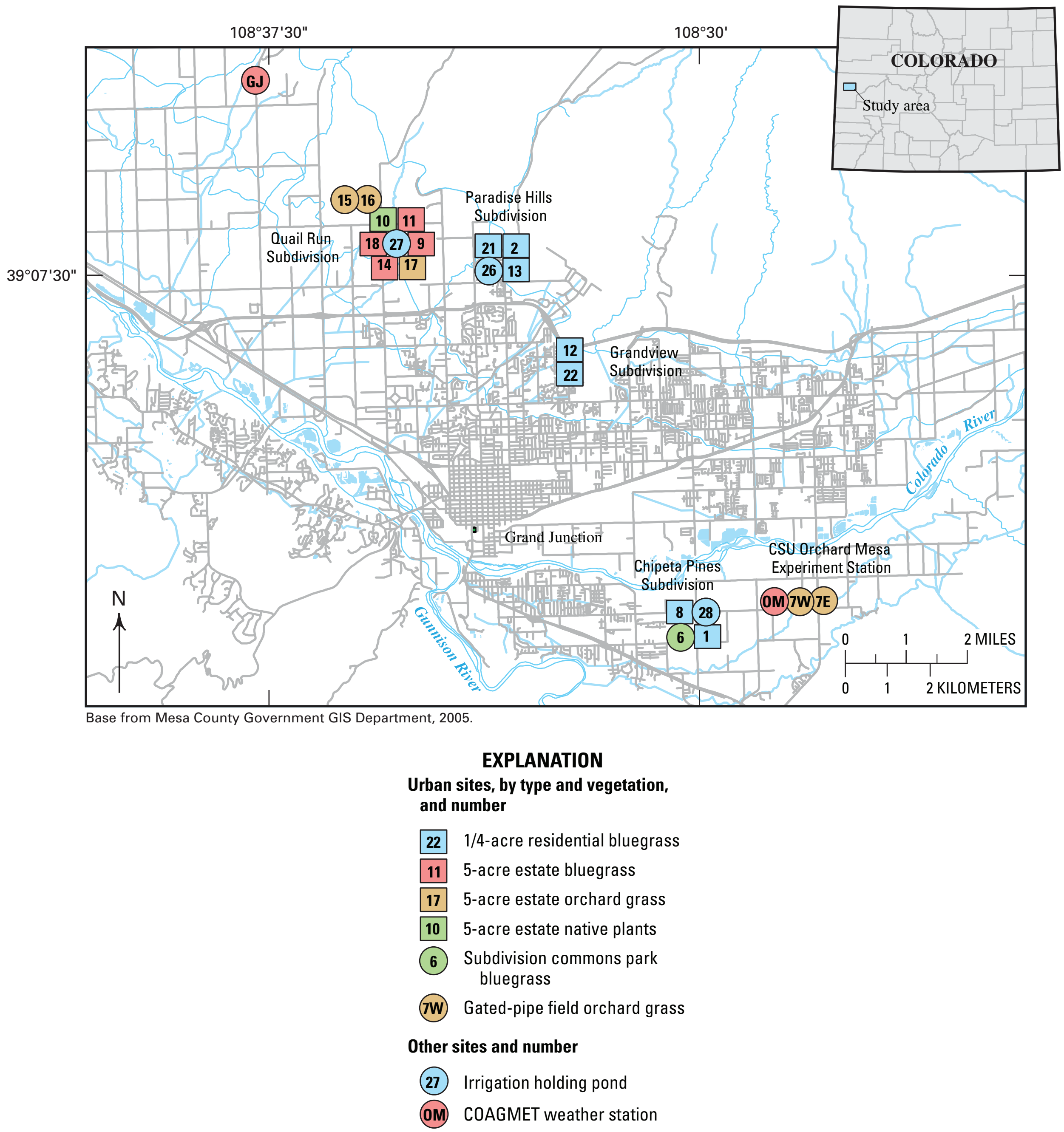


Figure 1. Urban study site locations in the Grand Valley, western Colorado.

Geologically, the Grand Valley is underlain by the Mancos Shale, which is a nonpoint source for salt and trace elements such as selenium (Butler and others, 1996). Deep percolation of irrigation water in the Grand Valley leaches considerable salt and selenium from Mancos Shale-derived soils and Mancos Shale bedrock. Upstream from the irrigated area of the Grand Valley, selenium concentrations are generally less than 1 part per billion (ppb), while downstream from irrigated areas, selenium concentrations commonly exceed 4.6 ppb, the State of Colorado chronic standard for aquatic life (Butler and others, 1996).

To estimate the effect of land-use conversion on deep percolation of water in this report, 21 urban sites in five areas of the Grand Valley were selected for study—three areas on the north side of the Colorado River and two areas on the south side. The 21 urban sites were studied for two irrigation seasons, in 2005 and 2006, resulting in a total of 30 irrigation seasons of data. All of the urban sites selected had been previously irrigated for agriculture (Dan Champion, Colorado State University, oral commun., 2005). An effort was made to associate these urban study sites spatially with those of the NRCS M&E, but because the ownership of the NRCS M&E sites was not recorded for privacy reasons, only generalized spatial correlations were possible. The NRCS M&E sites were within the same general areas of the Grand Valley that were selected for the urban study and had similar soil types and geology. The 1985–2002 NRCS M&E in the Grand Valley included 20 alfalfa-crop sites, resulting in a total of 67 irrigation seasons of data.

The urban site types included: (1) sprinkler-irrigated residential lawns planted with bluegrass on 1/4-acre residential lots (n = 7 sites); (2) sprinkler-irrigated 5-acre estates planted with bluegrass, orchard grass (a type of pasture grass), and native plant landscaping (n = 6 sites); (3) sprinkler-irrigated urban parks planted with bluegrass (n = 1 site); (4) small (1 to 2.5 acres) gated-pipe flood-irrigated urban pastures planted with orchard grass (n = 4 sites); and (5) small (0.2 to 1.1 acre) unlined perched irrigation-water holding ponds (n = 3 sites). Twelve of the 18 residential study sites had bluegrass, 5 had orchard grass, and 1 had native western Colorado xeriscape plants. Results were reported separately for the bluegrass-only sites and for all-vegetation type urban study sites.

Acknowledgments

Thanks are extended to the Board of Directors of the Mesa Conservation District for their support and oversight of the project.

Special thanks are due to all of the homeowners and irrigation managers who generously allowed us to monitor their irrigation practices and who kept handwritten logs for this study. Without their patience and enthusiasm, the study would not have been possible.

Thanks are also extended to the following individuals: Carl Zimmerman (Grand Junction Conservation Specialist for the Colorado State Conservation Board) for administration coordination with the Mesa Conservation District; Dawna Salazar (Mesa Conservation District Office Manager) who purchased equipment for the project; Jim Currier (NRCS Grand Junction District Conservationist) for mentoring, technical consultation, and liaison with the NRCS staff; Frank Riggle (NRCS Colorado Assistant State Conservationist for Water Resources) for consultation on evapotranspiration calculation methods and NRCS M&E data analysis; Dr. Curtis Swift (Colorado State University (CSU) Mesa County Extension Horticulturist) for technical consultations and the loan of weather stations; Ardith Blessinger (CSU County Extension) for performing the irrigation audits; Dr. Harold Larsen (Fruit Pathology Specialist at CSU Orchard Mesa Research Center) for evapotranspiration consultation, for providing pan evaporation data, and for finding archived NRCS M&E evapotranspiration (ET) data; Dan Champion (NRCS and CSU Extension, retired) for soil theory mentoring, for performing soil-moisture surveys, and for consultations on NRCS M&E data; Ryan Altenberg (NRCS Agricultural Engineer), who was very generous in loaning the GE Panametrics flow meter and consulting on irrigation practices; Terry Franklin (City of Grand Junction Water Services Superintendent) for aerial-photograph analysis of irrigated areas in two subdivisions; Dr. Michael Dukes (University of Florida, Gainesville) for consultations on residential irrigation research techniques; Dr. Frank Vignola (University of Oregon, Eugene) for help with conversion of historical meteorology data; Dr. Harold Duke (U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS), retired) for help with the CSU Colorado Agricultural Meteorological Network (COAGMET) Web site and for evapotranspiration support; Robert Wilson (USGS Hydrologist), for assistance with field construction; Paul Diaz (USGS Hydrologic Technician) for the pond acoustic depth survey; and Craig Muelot (USGS Hydrologic Technician) who was invaluable in accurately collecting and processing all of the field data for two seasons. Without Craig's attention to many details, the project could not have been completed.

Study Methods

Site Selection

The urban study included 21 sites, consisting of 1/4-acre residential lots (n = 7 sites), 5-acre estates (n = 6 sites), urban parks (n = 1 site), orchard (pasture) grass fields (n = 4 sites), and irrigation-water holding ponds (n = 3 sites) in the Grand Valley. A summary of site types for each irrigation season of the study is listed in table 1; nine sites were sampled in both 2005 and 2006. The two seasons of study resulted in 30 irrigation seasons of data. In addition, deep percolation and irrigation-water application for three whole subdivisions was estimated using mean site data from those subdivisions.

Table 1. Summary of urban study sites for 2005 and 2006 irrigation seasons, Grand Valley, western Colorado.

[n/a, not applicable]

Type of site	Vegetation	Total number of sites	Number of 2005 sites	Number of 2006 sites	Count of sites used for both seasons
¼-acre residential lot	Bluegrass	7	6	4	3
5-acre estate	Bluegrass	4	4	3	3
5-acre estate	Native plants	1	1	1	1
5-acre estate	Orchard grass	1	0	1	0
Commons park	Bluegrass	1	1	1	1
Gated-pipe field	Orchard grass	4	0	4	0
Irrigation holding pond	n/a	3	1	3	1
Totals		**21**	**13**	**17**	**9**

Residential Lots and Estates

Two categories of residential sites were selected for the study—residential lots of approximately 1/4 acre each and estates of approximately 5 acres each. Site characteristics for the residential lots and estates are summarized in table 2.

The residential lots were located in three subdivisions (Chipeta Pines, Paradise Hills, and Grandview), two on the north side of the Colorado River and one on the south side. The estates were all in one subdivision (Quail Run) on the north side of the river.

The residential lots and estates had only Kentucky bluegrass vegetation, with two exceptions. The first exception was one of the 5-acre estates, which had both a small bluegrass lawn and a large, irrigated, native plant landscaped area (rabbit brush, four-wing saltbush, sage, and various bunch grasses). Because the native-plant landscaping was sprinkler irrigated on a regular schedule, covered a major part of the site (0.56 acre), and because there is interest in the use of native plantings (xeriscaping) to conserve water, it was desirable to collect data on the native landscaped portion of the site. This estate was therefore divided into two separate study sites of bluegrass and native plantings. The second exception to bluegrass was at one of the 5-acre estates, which used orchard grass for the entire lawn area.

The area (in square feet) of all lawns and native-plant landscaped areas was determined using geographic information system (GIS) analysis of 2001–2005 aerial photographs provided by Mesa County. Irrigated areas containing shrubs, gardens, and trees were excluded, in addition to all non-irrigated vegetation at a site. Because of the variety of vegetation at the various residential sites, and because bluegrass is the predominant turf grass in the Grand Valley, two sets of water application and deep percolation results are reported: (1) bluegrass-only sites and (2) all-vegetation type sites.

All residential sites used commonly available underground pop-up sprinkler systems. Sprinkler heads include both impulse and spray types. All sites had automatic sprinkler-timers and used irrigation water rather than treated water. None of the residential sprinkler-timers included a rain sensor to turn off watering during rain events. Because the cost of irrigation water is low in the Grand Valley, cost was not considered a limiting factor for water application. For example, the irrigation water bill for one 5-acre estate was reported by the homeowner to be $170 for the 2005 season. The soil type for each site was determined from the NRCS Web Soil Survey Web site and was predominantly loam and clay loam (U.S. Department of Agriculture, 2007).

Urban Park

A 0.45-acre commons park at one subdivision (Chipeta Pines) was included in the study for two seasons (table 1). The commons park is on the south side of the Colorado River and had Kentucky bluegrass vegetation. The site used an underground sprinkler system controlled by an automatic irrigation timer without a rain sensor.

Table 2. Characteristics of urban study residential 1/4-acre lots and 5-acre estates, Grand Valley, western Colorado.

[CSU, Colorado State University; n/a, not applicable]

Site number	Year studied	Location	Site type	Irrigated acreage	Vegetation	Number of irrigation zones	Average flow for all sprinkler zones (gallons per minute)	Soil type
1	2005, 2006	Chipeta Pines	1/4-acre residential lot	0.12	Bluegrass	10	12	Loam
2	2005	Paradise Hills	1/4-acre residential lot	0.12	Bluegrass	7	22	Clay loam
6	2005, 2006	Chipeta Pines	Commons park	0.45	Bluegrass	3	74	Loam
7W	2006	CSU Orchard Mesa	Gated-pipe field	0.99	Orchard grass	n/a	n/a	Clay loam
7E	2006	CSU Orchard Mesa	Gated-pipe field	0.99	Orchard grass	n/a	n/a	Clay loam
8	2005, 2006	Chipeta Pines	1/4-acre residential lot	0.06	Bluegrass	1	30	Loam
9	2005, 2006	Quail Run	5-acre estate	1.12	Bluegrass	12	30	Clay loam
10	2005, 2006	Quail Run	5-acre estate	0.56	Native	2	30	Clay loam
11	2005, 2006	Quail Run	5-acre estate	0.14	Bluegrass	3	27	Clay loam
12	2005, 2006	Grandview	1/4-acre residential lot	0.05	Bluegrass	2	16	Loam
13	2005	Paradise Hills	1/4-acre residential lot	0.14	Bluegrass	5	14	Clay loam
14	2005	Quail Run	5-acre estate	1.00	Bluegrass	13	52	Clay loam
15	2006	Near Quail Run	Gated-pipe field	0.95	Orchard grass	n/a	n/a	Loam
16	2006	Near Quail Run	Gated-pipe field	2.13	Orchard grass	n/a	n/a	Clay loam
17	2006	Quail Run	5-acre estate	1.70	Orchard grass	16	43	Clay loam
18	2005, 2006	Quail Run	5-acre estate	0.82	Bluegrass	7	44	Clay loam
21	2006	Paradise Hills	1/4-acre residential lot	0.10	Bluegrass	6	15	Clay loam
22	2005	Grandview	1/4-acre residential lot	0.05	Bluegrass	2	23	Loam
23	2005, 2006	Chipeta Pines	Whole subdivision	6.03	Bluegrass	n/a	n/a	Loam
24	2005, 2006	Paradise Hills	Whole subdivision	34.9	Bluegrass	n/a	n/a	Clay loam
25	2005, 2006	Quail Run	Whole subdivision	41.6	Bluegrass/native	n/a	n/a	Clay loam

Gated-Pipe Irrigated Fields

One of the purposes of the urban study was to measure deep percolation from small, urban fields that grow orchard grass and use furrow irrigation supplied by a gated-pipe system. The gated-pipe irrigation infrastructure is usually a holdover from agricultural use of the fields. These pastures are typically adjacent to homes and are commonly 1 to 2 acres in size. No suitable sites were found for the 2005 season, but for 2006, four sites (sites 7W, 7E, 15, and 16 in table 2) were located. Sites 15 and 16 are a pair of privately owned fields (0.95 and 2.13 acres) used to grow orchard grass for horses. Site 7 is a test field (1.98 acres) growing orchard grass at the Colorado State University (CSU) Western Colorado Research Center in Orchard Mesa. Because site 7 was always watered in halves, it was treated as two distinct sites, 7 West (7W) and 7 East (7E). All four fields were planted in orchard grass, a bunch grass widely used for forage in the Grand Valley. The privately owned fields were grazed by horses periodically during the season, while the CSU field was used to produce hay.

Irrigation-Water Holding Ponds

Another purpose of this study was to calculate seepage from selected unlined irrigation holding ponds. These ponds are used by subdivisions to store irrigation water for onsite sprinkler irrigation pumping systems. Three subdivision ponds (Paradise Hills, Quail Run, and Chipeta Pines) were observed (table 3). The ponds receive gravity-fed water by underground pipe from the irrigation canals. The ponds contain water during the irrigation season and are allowed to empty naturally when the irrigation season ends about November 1. One pond was observed for the 2005 season, and three were observed for the 2006 season.

It was assumed that these holding ponds were perched above the water table; thus, ground-water inflow could be ignored. The observation that all three ponds are virtually dry during the winter supports this assumption, but this may not hold true during the irrigation season. One of the ponds (Paradise Hills) is approximately 150 yards from the irrigation canal and is lower than the canal. Anecdotal information from the Paradise Hills irrigation manager suggests that properties adjacent to and lower than the canal receive seepage, which affects their lawns during the summer (Tom Mahoney, homeowner, oral commun., 2005). It thus cannot be ruled out that seepage from the canal raises the level of ground water surrounding the pond. This could have the effect of reducing the predicted pond seepage during the irrigation season. The ponds at Quail Run and Chipeta Pines are farther from their respective supply canals (1 mile and 0.7 mile, respectively) and are probably not affected by any canal seepage. Research conducted by the Bureau of Reclamation on canal seepage in the Grand Valley indicated that canal seepage rates varied greatly, depending on testing procedures and location (Bureau of Reclamation, 1986).

Data Collection

Residential Lots and Estates

Data collection at the home sites included handwritten irrigation logs and digital data loggers that recorded sprinkler-timer irrigation events and system water pressure. Table 4 summarizes the data-collection methods used for residential lots and estates. Homeowners were encouraged to maintain normal irrigation practices during the study. In all cases, the homeowners were cooperative and friendly during the visits.

Site Visits

Each site was visited at least once a month from April through November. Data loggers were checked and downloaded, homeowner's handwritten logs were digitally scanned, photographs of the lawn were taken, and visual observations of the lawn condition were recorded. Soil-moisture core samples were collected for gravimetric analysis, and a subjective visual and hand-feel estimate of soil moisture was made using traditional agricultural field techniques (Leopold, 2003).

Irrigation Event Logs

For the 2005 season, the primary record of irrigation events was a handwritten log kept by the homeowner. This irrigation event log recorded the sprinkler-timer irrigation schedules, including dates, time, and duration of irrigation events by zone. The homeowners mostly were cooperative and timely in maintaining these logs. Field personnel independently observed and wrote down the sprinkler-timer programs at each monthly visit when the timer was accessible.

For the 2006 season, 22-channel digital data loggers were designed and built to record directly the actual irrigation events for each sprinkler zone (fig. 2). Each 24-volt alternating

Table 3. Characteristics of urban study irrigation-water holding ponds.

[Surface area, surface area of water when pond is at capacity]

Subdivision/ site number (fig. 1)	Surface area (acres)	Capacity (acre-feet)	Maximum depth (feet)	Years studied	Pond lining material	Soil type
Paradise Hills/26	1.09	2.90	4.49	2005, 2006	None	Clay loam
Quail Run/27	0.34	1.37	6.76	2006	None	Clay loam
Chipeta Pines/28	0.17	0.55	5.25	2006	None	Loam

Table 4. Data-collection methods at urban study 1/4-acre residential lots and 5-acre estates.

[CSU, Colorado State University; USGS, U.S. Geological Survey]

Data collection method	Collection frequency	Data source
Sprinkler-timer log (2006 only)	Every minute	Data logger on sprinkler-timer
Handwritten log	With changes in irrigation schedule	Homeowner
Water pressure log	Every 2 minutes	Data logger on irrigation system input pipe
Flow rate per zone	Start and end of season	Field measurement by USGS
Measured precipitation	Every 60 minutes at 6 sites	4 local weather stations and 2 CSU weather stations
Evapotranspiration	Daily calculation from climate data	2 CSU weather stations
Irrigation audit	Once per site at beginning of season	CSU County Extension Agent
Soil moisture	Start and end of season (2005), monthly (2006)	USGS staff sample collection
Visual observation of lawn	Monthly	USGS staff

current (AC) signal from the timer that activates a zone valve was connected to an input channel. Every 60 seconds the data logger scanned all the channels but recorded only to the digital log when a valve changed state. This resulted in a greatly simplified and compressed digital log. In addition, the homeowners were asked to continue to maintain a handwritten log of their irrigation events as a backup in case of data logger failure.

Water Pressure Logs

Water pressure was recorded every 60 seconds using a solar-powered digital data logger at the irrigation water-supply pipe to each irrigation system (fig. 3). This provided different information, depending on the type of site. Because the 1/4-acre residential sites received irrigation water from a centrally pressurized system, water pressure at those sites provided an indication of whether the central supply was available and served as a cross-check against the sprinkler-timer events to ensure that the logged event actually resulted in water application to the lawn. For example, if the sprinkler-timer triggered an irrigation event but water pressure was zero, no water was applied. All of the 5-acre estate sites received gravity-fed irrigation water by underground pipe, which was then pressurized by a local water pump at each home. A master valve at the system input was opened by the timer during the irrigation event. For the 5-acre sites, water pressure was an indication that the system was delivering water and again served as a cross-check of the sprinkler-timer events.

Flow Rate Per Zone

By knowing the average water-flow rate per zone, a calculation of the total quantity of water delivered during an irrigation event can be made by multiplying the zone flow rate by the zone event duration. To determine average flow rate per zone in cubic feet per second (ft^3/s), a GE Panametrics PT878 noninvasive acoustic flow meter was attached to the main irrigation water input pipe for a system. A 5-minute cycle was run for each zone, with the flow meter logging the flow rate every 2 seconds. In 2005, water inflow rates for each zone at every site were measured in April and again in September. No significant differences in average flow rates were found in the second set of measurements, indicating flow rates may have been consistent through the irrigation season. In 2006, sites were measured in April.

Water pressure was simultaneously recorded during the flow test by using water-pressure data loggers to determine the variability in supply pressure and to determine an average pressure. Subsequent comparison of these average system water pressures with recorded daily pressures during the season indicated no substantial variations in average pressure at the sites. For this reason, it was not necessary to correlate water pressure with the quantity of water applied during individual irrigation events.

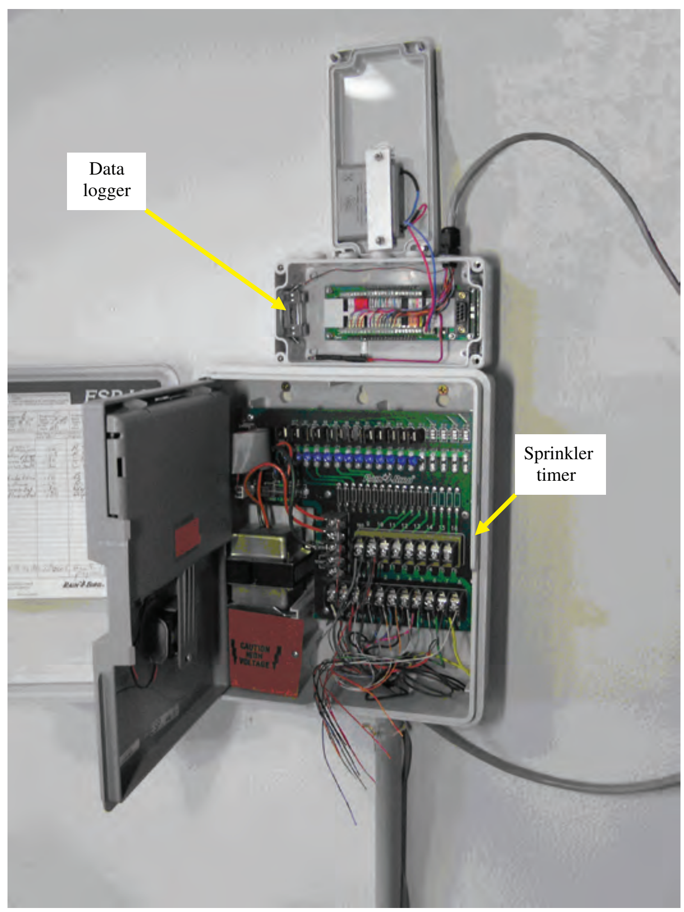


Figure 2. Sprinkler-timer data logger attached to sprinkler timer.

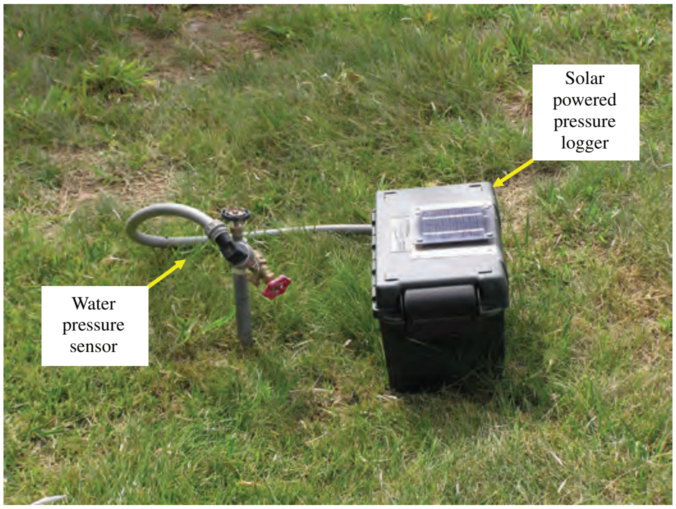


Figure 3. Irrigation system pressure logger in the field.

Precipitation

In each of the four study subdivisions, precipitation was measured hourly with a Spectrum Technologies weather station that incorporated a digital data logger. The subdivision precipitation gages were checked for calibration at the beginning of the 2005 season. In addition, two Internet-accessible CSU COAGMET Campbell Scientific weather stations (Grand Junction and Orchard Mesa; fig. 1) provided published hourly precipitation.

To determine the portion of precipitation available for infiltration into the ground, the measured precipitation data were corrected for runoff to determine “effective” precipitation using the U.S. Army Corps of Engineers Hydraulic Engineering Center-Hydrologic Modeling System (HEC-HMS) (U.S. Army Corps of Engineers, 2006). The HEC-HMS model accounts for rainfall intensity over time to estimate the runoff. In general, precipitation events exceeding 0.10 inch caused runoff, with intense events of short duration (less than 2 hours) causing the most runoff. Unless measured precipitation data are being discussed, precipitation in this report always refers to effective precipitation.

Soil-Moisture Core Samples

As a cross-check against calculated soil-moisture balances (see “Daily Soil-Moisture Balance” section of this report), soil-moisture samples were collected two times at each site in 2005, and monthly in 2006. The ASTM International laboratory methods for gravimetric soil-moisture collection were followed (ASTM International, 2006). Each sample consisted of a 1-inch diameter core of the top 12 inches of soil. A grid was overlaid on an aerial photograph of each site, and 10 sample locations were randomly selected each month at each site. The 10 cores were then composited into a single sample for analysis.

In the gravimetric method, a soil sample is weighed while wet (wet weight), then oven dried at 105°C for 24 hours, and then weighed dry (dry weight) (ASTM International, 2006). The weight lost during oven drying represents the initial soil moisture of the sample.

Soil moisture is calculated (Brady and Weil, 2002):

$$\theta_v = \frac{\theta_g \times \rho_{soil}}{\rho_{water}} \times d \qquad (1)$$

where

θ_v is volumetric water content for sample depth d (inches),

ρ_{soil} is bulk density of soil (g/cm^3),

ρ_{water} is density of water (1 g/cm^3),

θ_g is gravimetric soil moisture = $\dfrac{\text{wet weight} - \text{dry weight}}{\text{dry weight} - \text{tare}}$,

and

d is depth of soil sample (inches).

Bulk soil density for each site was calculated in 2006 for all sites for both years by using a composite sample of known volume. Bulk soil density is determined by dividing the dry weight of the sample by its volume.

Urban Park

Site Visits

The subdivision commons park was visited monthly to download data loggers, scan the handwritten logs, and collect soil core samples.

Irrigation Event Logs

The subdivision commons park was controlled by a standard residential Rainbird controller and was instrumented with a sprinkler-timer data logger. The handwritten log of irrigation events was maintained by the irrigation manager for the subdivision in case a backup to the data logger was needed.

Water Pressure Logs

No log of water pressure was kept for this site because of limitations in the site piping.

Flow Rate Per Zone

Flow rate per zone for the subdivision commons park was measured with the GE acoustic flow meter in the same manner as at the residential sites.

Precipitation

Precipitation data for the subdivision commons park were collected by the weather station for that subdivision. Effective precipitation was calculated by subtracting estimated runoff from the raw precipitation values.

Soil-Moisture Core Samples

Soil-moisture core samples for the subdivision commons park were collected using the same methods and schedule as for residential sites. Bulk density also was determined in the same manner as described for residential sites.

Urban Gated-Pipe Fields

Site Visits

The urban gated-pipe fields were visited monthly in 2006 to download data loggers, scan handwritten logs, and collect soil-moisture core samples.

Irrigation Event Logs

The two privately owned gated-pipe fields (sites 15 and 16) had an existing dedicated Bureau of Reclamation (BOR) totalizing flow meter at their shared irrigation water-supply lateral line. Because only one field was watered at a time (controlled by manually operated valves), inflow per field could be accurately recorded by the flow meter. The homeowner logged the flow meter reading at the start and end of watering for each field, as well as the dates and times of watering. The two privately owned fields had 12-inch broad-crested flumes installed in the tail-water ditches (fig. 4) for measuring runoff (tail-water flow) from the bottom of the fields.

For inflow data to the CSU-operated gated-pipe fields (sites 7E and 7W), USGS installed a totalizing flow meter in the supply pipe to the field. The 12–inch broad-crested flume was installed at the downstream end of the field. A manual log was kept by the CSU staff to record irrigation event times, event durations, and beginning and ending flow-meter readings.

Figure 4. Broad-crested flume used to measure gated-pipe field tail-water runoff.

The field was always watered in halves, with each half being watered on consecutive days. For analysis purposes, these two field halves were treated as two separate sites.

The broad-crested flumes have a rating that allows the depth of water in the throat of the flume to be converted to flow in cubic feet per second (ft^3/s). A data logger with a pressure sensor in a stilling well was used with each flume to record water depth in the throat of the flume. The difference between inflow and tail-water runoff yields net water applied to the field. Subtraction of cumulative ET during the event from the net water applied then gives deep percolation.

At the two privately owned fields, a digital pressure gage was initially installed to record stage at each flume, but after the first four irrigation events both pressure gages failed. For the remaining irrigation events at each of the two fields, runoff was estimated for each event by using linear regression equations (Helsel and Hirsch, 2002), which were derived from inflow compared to runoff data for the four events with good (pressure gages were working) runoff records (fig. 5*A*, *B*). The regression equations are (a) $y = 0.7635x - 0.1868$, and (b) $y = 0.0373x + 0.031$ (Pearson correlation coefficients $R^2 = 0.7319$, $R^2 = 0.2172$, respectively). Note that the axis scales are different in both graphs to allow for maximum resolution of the data points.

At the CSU-operated gated-pipe fields, the pressure gage stage recorder successfully recorded the first irrigation event for each field. Due to equipment failure, no runoff data were recorded for the next three irrigation events at each field. For the final event at each field, a strip-chart stage recorder was installed that collected good flume-stage data. A linear regression equation (Pearson correlation coefficient $R^2 = 0.9999$) (fig. 5*C*) was created using the four known good data points to estimate runoff for the three irrigation event pairs without measured runoff data. The regression equation is (c) $y = 1.4774x - 0.8834$. Note that the axis scales are different in each of the graphs to allow for maximum resolution of the data points.

Precipitation

Precipitation for the two privately owned gated-pipe fields was compiled from the CSU COAGMET Grand Junction weather station (approximately 3 miles from site). Precipitation for the CSU Orchard Mesa Research Center was compiled from the onsite CSU COAGMET Orchard Mesa weather station (Colorado State University, 2005–2007). Effective precipitation was calculated by subtracting estimated runoff from raw precipitation values.

Soil-Moisture Core Samples

For the three gated-pipe fields, soil-moisture core samples were collected using the same methods and schedule as for residential sites. Bulk density also was determined in the same manner as described for residential sites.

Irrigation-Water Holding Ponds

A standard USGS staff plate was installed in each pond to allow measurement of pond stage, and the datum (elevation) of the staff plate was surveyed. At the end of the irrigation season, after the inflow of water to the pond had ceased, the stage levels were manually recorded approximately weekly.

Daily pan evaporation data were obtained during the same period at the CSU Orchard Mesa Research Center. The Research Center operates the only Class A evaporation pan in the Grand Valley and is a distance of approximately 2, 7, and 9 miles, respectively, from the pond sites. Pan evaporation overstates actual lake evaporation and requires downward adjustment by use of a pan coefficient multiplier. For this study, the measured pan evaporation values were multiplied by 0.70, which is the published pan coefficient for western Colorado (Ward and Trimble, 2004). Precipitation data were obtained from the nearest CSU COAGMET Grand Junction and Orchard Mesa weather stations. Effective precipitation values were calculated by subtracting estimated runoff. No water accumulated in the ponds over the winter, after the canal inflow was shut off, so ground-water inflow probably does not occur.

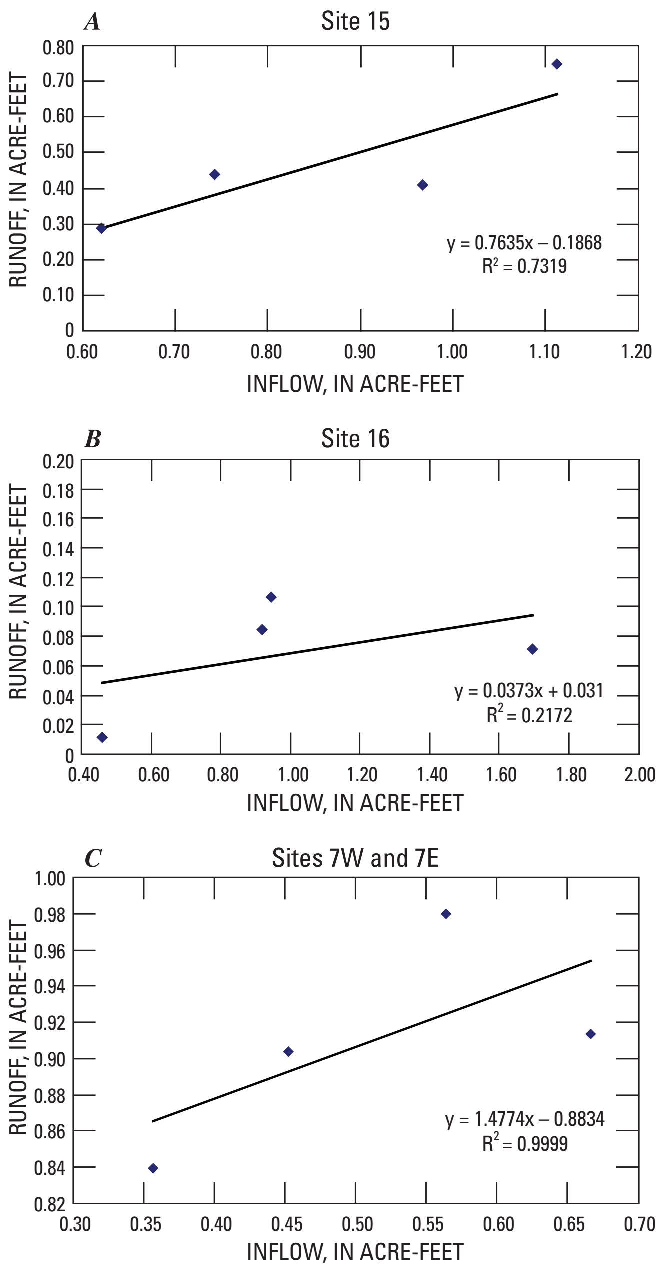


Figure 5. Runoff linear regression equations for gated-pipe fields (*A*) site 15, (*B*) site 16, and (*C*) sites 7W and 7E, Grand Valley, western Colorado. Note that the axis scales are different on the three graphs.

2005 Irrigation Field Season

The 2005 irrigation field season started on April 15 and ran through November 29. Monitoring equipment was installed and irrigation water was available to all sites by April 15, but the initial soil-moisture samples were not collected until various dates in May. Because the initial soil moisture is the starting value for the daily soil-moisture balance calculations, it was assumed that the initial soil moistures were at field capacity on April 15 (Dan Champion, Colorado State University, oral commun., 2005). A late-season soil-moisture sample also was collected at each site for verification of soil moisture. The Paradise Hills pond was monitored for 22 days starting November 1.

At the end of the 2005 season, the data sets for six sites (numbers 3, 4, 5, 17, 19, and 20), composed of four bluegrass sites, one orchard grass site, and one native-plant site, were excluded from analysis because the handwritten logs were incomplete in three cases, and the others had excessive handwritten log errors when compared with the pressure logs.

2006 Irrigation Field Season

The 2006 irrigation field season ran from April 1 through November 25. All monitoring equipment was in place, and initial soil-moisture samples were collected for all sites by April 1. Monthly soil-moisture samples were collected throughout the season. In November, an additional soil sample with a known volume was collected at each site (2005 and 2006) to calculate bulk density values.

Pond stage data were obtained at all three pond sites (Paradise Hills, Quail Run, and Chipeta Pines) for 25 days starting on November 1, from the shutdown of the irrigation canals until freezing of the CSU evaporation pan. At the end of the 2006 season, all sites had acceptable data sets, and no sites were excluded from analysis.

Deep Percolation Calculations

Deep percolation was calculated in two ways:

- Daily soil-moisture balance calculation for residential lots, estates, and gated-pipe fields, and
- Pond-water balance calculation for irrigation-water holding ponds.

Calculation of the daily soil-moisture balance is preferable for reasons of accuracy, although collecting daily data requires an intensive effort. For this study, it was possible to obtain daily data for all residential sites, the commons park, and all gated-pipe field sites. Pond-water balance calculations were made by measuring stage changes in the pond during an observation period, while accounting for pan evaporation and total daily precipitation.

Daily total deep percolation calculations require the determination of a soil-moisture balance for the top 12 inches of soil at each study site. The bluegrass and orchard grass at the study sites had roots that were typically less than 6 inches in depth, so the top 12 inches of soil was considered to encompass adequately the rooting depth of the grass. One site in the study contained native plants that probably had roots deeper than 12 inches, but this was not accounted for in soil-moisture calculations.

Soil-moisture balance is the sum of all inflows and all outflows into the soil column. The inflows include the portion of rainfall and irrigation applications that infiltrate the soil, as well as any ground-water infiltration. For the purpose of this study, ground-water inflow was assumed negligible and was not accounted for. The outflows include evapotranspiration (ET), surface runoff, and deep percolation.

Units of Measure

For agricultural use, irrigation-water application is traditionally reported in units of inches or acre-feet (Brady and Weil, 2002). An inch is the amount of applied water that would cover any given area an inch deep. To obtain a volume of water from inches, the area of coverage is required. Volume of irrigation water also is measured in acre-feet, which is the amount of water that would cover an area of 1 acre to a depth of 1 foot. All values of irrigation application, rainfall, and deep percolation for this study are reported in units of either inches or acre-feet.

Soil Moisture

A soil column is analogous to a sponge with a certain capacity to hold water in equilibrium. For agricultural purposes, there are several components of soil-moisture calculations (fig. 6) (Brady and Weil, 2002). Field Capacity (FC) is the quantity of water in inches remaining after a saturated column of soil has been allowed to drain (typically for 24 hours) so that capillary forces holding the water in place are balanced by the force of gravity drawing the water downward. Soil moisture in excess of FC is commonly considered to drain from the soil column to become deep percolation. Permanent Wilting Point (PWP) is an amount of water in the soil column (in inches) below which the water is unavailable to the plant. Between FC and PWP is the Total Available Water (TAW) to the plant. Only a portion of the TAW is considered to be Readily Available Water (RAW). The percentage of TAW that is RAW is typically 40 percent and is a function of soil type (Duke, 1991). The transition point between readily available and not readily available water is called the ET stress point in this report.

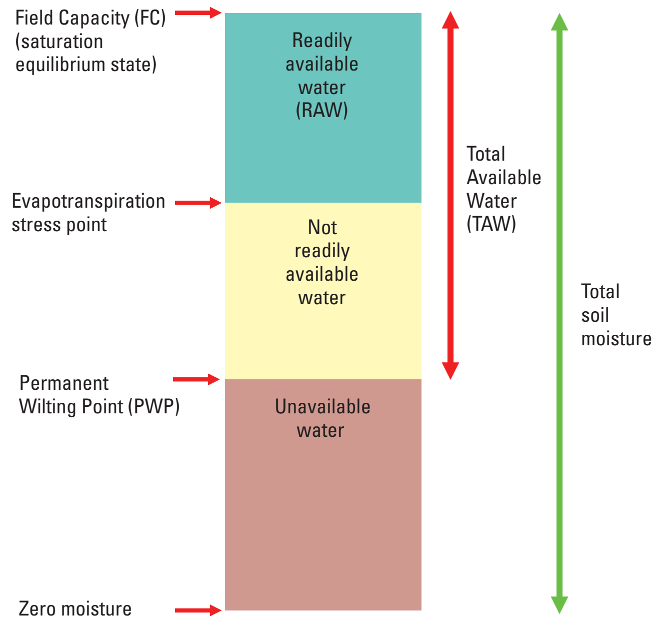


Figure 6. Schematic diagram of soil-moisture characteristics.

FC and PWP values are soil specific. For typical clay-loam soils such as those in the study area, FC = 4.59 inches of water and PWP = 2.54 inches (Duke, 1991). For loam soils, the published value for FC = 4.11 inches of water, and PWP = 1.60 inches. Some empirical corrections were made to FC and PWP at several sites and are discussed later in the section on Field Capacity Corrections.

Evapotranspiration

Evapotranspiration (ET) caused most of the daily soil-moisture loss at the study sites. For example, an ET value for a given day of 0.2 inch means that the crop and soil will lose 0.2 inch of water that day due to ET processes. The ET can be calculated for any time period: hourly, daily, weekly, or for an entire season. The ET has two components: (1) direct evaporation of water from the soil and plant surfaces, and (2) transpiration of water through plant tissues.

ET is an energy process driven by solar heating and wind (advection) (Allen and others, 1998). ET is not commonly measured directly in agriculture settings. Rather, equations have been developed to calculate ET energy balance from meteorological data. Input data usually include solar radiation, windspeed, air temperature, and humidity. Various calibration factors are applied to tailor the equation to become crop and soil specific and to account for local meteorological conditions.

Urban Study Evapotranspiration Calculation

This study uses the Penman-Monteith (P-M) ET equation, which has been adopted by the United Nations Food and Agricultural Organization (FAO) and is defined in their FAO Irrigation and Drainage Paper 56 (FAO-56) (Allen and others, 1998). Although several ET equations and variants have been developed, the FAO-56 P-M equation is currently (2008) considered to be the world standard. The FAO-56 P-M ET equation, while fully defined in the FAO-56 paper, is too complex to describe in detail here, and ET is normally calculated using software such as REF-ET (Allen, 2001). Each variant of the ET equation is based on a particular reference crop (either alfalfa or turf grass) and yields what is called a reference ET value. Traditionally, the alfalfa reference is called ET_r and the turf-grass reference is called ET_o. The FAO-56 P-M equation is referenced to turf grass, which makes it well suited for use in this study. Agricultural ET equations are most often referenced to alfalfa.

To obtain the ET value for a particular crop (such as corn or wheat) from the reference ET, a crop coefficient is used to multiply the reference ET value. The ET equation used in this study is:

$$ET_c = [(K_r \times K_e) + (K_s \times K_{cb})] \times ET_o \qquad (2)$$

where

ET_c is the crop-specific evapotranspiration,

$[(K_r \times K_e) + (K_s \times K_{cb})]$ is the composite crop coefficient,

K_r is the soil evaporation stress factor,

K_e is the “soil evaporation coefficient” due to soil evaporation,

K_s is the crop stress factor,

K_{cb} is the “basal crop coefficient” due to plant transpiration,

and

ET_o is the reference evapotranspiration.

Crop coefficients can be simple or complex, depending on the need for accuracy. The FAO-56 P-M method allows for the use of a dual crop coefficient with two terms: (1) a term for plant transpiration, K_{cb}, the “basal crop coefficient” and (2) a term for soil evaporation, K_e, the “soil evaporation coefficient.” This dual crop coefficient technique allows for a separate determination of the effects on ET from the soil and the crop characteristics and is considered more accurate.

The basal crop coefficient, K_{cb}, is a calculated constant value (from a lookup table) for the particular crop (Allen and others, 1998, chapter 7). This constant value is then modified daily using a standard equation to account for local mean daily windspeed, mean daily minimum relative humidity, and mean plant height. The daily windspeed and relative humidity data for this study were compiled from local meteorological data from the nearest CSU COAGMET weather station. The basal crop coefficient lookup table value for turf grass is 0.90 (Allen and others, 1998, chapter 7).

The soil evaporation coefficient, K_e, for a given crop is calculated in a standard equation to account for the percentage of exposed soil and the amount of water depleted from the soil. K_e is limited by a calculated upper limit for the total evaporation and transpiration, which is possible from a cropped surface (Allen and others, 1998, chapter 7).

A technique to gain further ET accuracy is to correct each of the dual terms of the crop coefficient for the “stress condition” of the crop and soil, respectively (Allen and others, 1998, chapters 7 and 8). The crop stress factor, K_s, is based on the premise that when soil moisture is in the RAW region of the TAW (see fig. 7*A*) between FC and PWP, ET functions normally, as calculated by the basic FAO-56 P-M equation (fig. 7*A*). When soil moisture falls below the ET stress point, however, the plant begins to conserve moisture and transpires less. It is assumed that below the RAW region, the ET declines linearly to zero at the PWP. Typical RAW for clay loams is 40 percent of TAW (Duke, 1991).

Similar to the crop stress factor, a soil evaporation stress factor, K_r, is based on the premise that due to the degree of wetness of the soil surface, there is a Readily Evaporable Water (REW) region between FC and PWP similar to the RAW zone. When soil moisture is within the REW, soil evaporation is predicted by the basic FAO-56 P-M equation (fig. 7*B*). Below the ET stress point, soil evaporation declines linearly to zero at the PWP. REW is typically considered to be 40 percent of TEW (Allen and others, 1998, chapter 7).

The crop stress and soil evaporation coefficients have a substantial effect in reducing calculated daily ET when soil moisture is not maintained in the optimum range for evaporation and transpiration.

Natural Resources Conservation Service Monitoring and Evaluation Evapotranspiration Calculation

Descriptions of the ET calculation methods used in the NRCS M&E were not readily available. By interviewing the personnel (now mostly retired) from that study, it was determined that two ET equations were used during different periods, with a probable crossover time of 1989. From 1985 until 1988, a software program called SCHED was used. SCHED was developed by Dale Heerman and associates at the Fort Collins Agricultural Research Service (ARS) office of USDA, and used a modified Penman alfalfa-crop reference ET equation with calibration coefficients for Scotts Bluff, Nebraska (Buchleiter and others, 1992). This equation

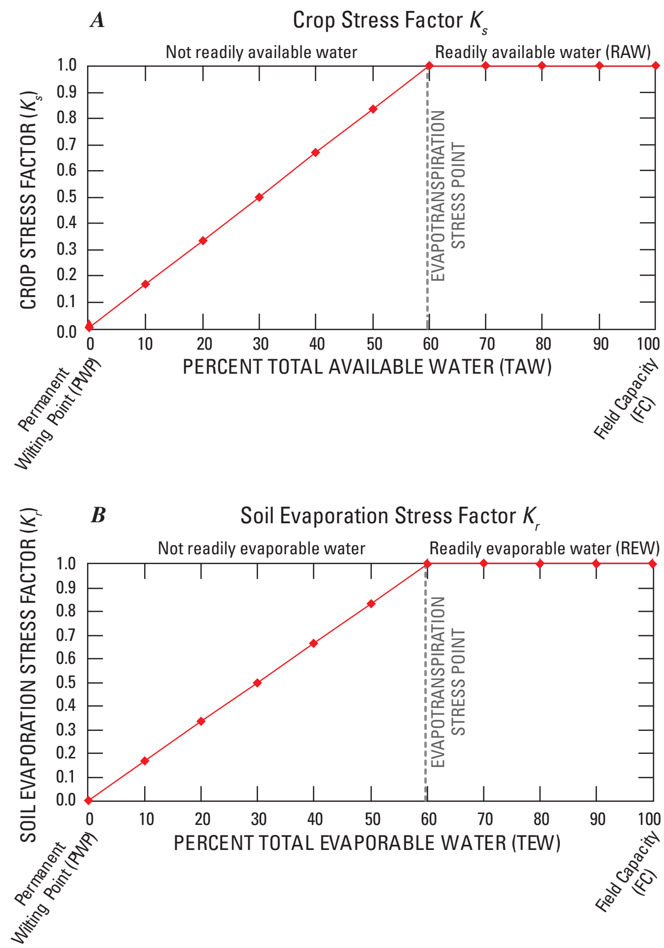


Figure 7. (*A*) Crop stress factor K_s for transpiration portion of composite crop coefficient, and (*B*) soil evaporation factor K_r for evaporation portion of composite crop coefficient.

was designed primarily for center pivot irrigation in eastern Colorado; however, applicability to the arid western Colorado climate is not known.

In 1989, the NRCS M&E apparently began using an alfalfa-referenced Jensen Haise ET equation on a personal computer (PC) spreadsheet (Harold Larsen, Colorado State University, oral commun., 2006). No details are known about the adjustment coefficients used with the Jensen Haise equation (Duke, 1991). A time-dependent crop coefficient based on stage of crop growth was used.

For the NRCS M&E, season-total ET values were calculated per monitored site for the years 1985 through 1998. No ET data were calculated per site for 1999 through 2002. One spreadsheet from 1999 was available that contained daily ET values from 1989 through 1999, calculated using data from two NRCS-operated weather stations (CSU Fruita and Orchard Mesa Experiment Stations).

To test the validity of the NRCS M&E ET values, new ET values were calculated for 1993 to 1999 using archived meteorological data from the CSU COAGMET Web site (Colorado State University, 2005–2007) and the REF–ET software program (Allen, 2001). The REF–ET program provides ET values simultaneously from a number of different ET equations. By linear regression, it was determined that the NRCS M&E ET values were closely matched to the ET values generated with the 1982 Kimberly-Penman Equation (Pearson correlation coefficient $R^2 = 0.99$). The CSU COAGMET Web site also uses the 1982 Kimberly-Penman equation for published daily ET values.

Further comparison, using a scatterplot of the 1982 Kimberly-Penman ET values with ET results for the same period of years calculated in REF–ET with the FAO-56 Penman-Monteith equation (the ET method used in this study), yielded a Pearson correlation coefficient of $R^2 = 0.97$. The 1982 Kimberly-Penman method was thus an analytical bridge between the NRCS M&E ET method and the present study method. By this indirect method, it was determined that the historical NRCS M&E ET values for the time period of 1993 to 1999 were an acceptable match with the urban study ET values, and the calculation method was close enough to the current study ET method for the purposes of deep percolation comparisons.

Daily Soil-Moisture Balance

To calculate daily deep percolation, it is necessary to determine if soil moisture at the end of each day is greater than the field capacity. This is done by calculating a preliminary daily soil-moisture balance, disregarding deep percolation. Calculated soil moisture is then compared to the field capacity, and if the soil moisture is greater than field capacity, the difference is assumed to be deep percolation.

The equation for preliminary daily soil-moisture balance (ignoring ground-water inflow and deep percolation) is:

$$balance_{preliminary} = balance_{previous} + precipitation_{daily\ effective} + irrigation_{daily\ net} - ET_c \quad (3)$$

where

$balance_{preliminary}$ is the soil-moisture balance at the end of the current day before deep percolation is taken into account (inches),

$balance_{previous}$ is the soil-moisture balance at the end of the previous day (inches),

$precipitation_{daily\ effective}$ is daily measured precipitation minus predicted runoff (inches),

$irrigation_{daily\ net}$ is the irrigation inflow multiplied by irrigation efficiency minus any tailwater flow (irrigation efficiency is the percentage of irrigation water flowing into an irrigation system that actually is applied to the plants and the ground) (inches),

and

ET_c is the daily crop-specific evapotranspiration corrected for crop stress (inches).

The daily deep percolation is then calculated:

$$deep\ percolation_{daily} = moisture\ balance_{preliminary} - field\ capacity \quad (4)$$

where

deep percolation$_{daily}$ is the daily deep percolation (inches). (Negative values of deep percolation are treated as zero),

moisture balance$_{preliminary}$ is the moisture balance before deep percolation is subtracted (inches),

and

field capacity is the saturated water-holding capacity of soil (a constant in inches).

The ending soil-moisture balance, *balance*$_{ending,}$ is calculated as:

$$balance_{ending} = balance_{preliminary} - deep\ percolation_{daily} \quad (5)$$

where

balance$_{ending}$ is the daily ending soil-moisture balance (inches),

balance$_{preliminary}$ is the daily soil-moisture balance before deep percolation is subtracted (inches),

and

deep percolation$_{daily}$ is the daily deep percolation (inches).

By incorporating the acreage, the volume of daily deep percolation in acre-feet can be calculated as:

$$deep\ percolation_{acre\text{-}feet} = \frac{deep\ percolation_{inches} * irrigated\ areas_{acres}}{12_{inches\ per\ foot}} \quad (6)$$

where

deep percolation$_{acre\text{-}feet}$ is the deep percolation converted to acre-feet,

deep percolation$_{inches}$ is the deep percolation in inches,

and

irrigated area$_{acres}$ is the acreage of irrigated area.

Daily Soil-Moisture Balance Graph

To visualize the daily changes in soil-moisture balance for a site, a graph was created for each site. A typical plot of daily soil moisture for bluegrass on a 1/4-acre residential site is shown in figure 8. The vertical axis represents inches of water, with positive values indicating inflows and negative values indicating outflows. The horizontal axis represents days of the irrigation season.

The inflows and outflows represented in this graph are:

- Orange trace line indicates the calculated daily soil-moisture balance;
- Blue vertical bars indicate the effective precipitation (measured less predicted runoff);
- Green vertical bars indicate the irrigation application, corrected for irrigation efficiency and tail-water flow;
- Blue-grey solid trace indicates the evapotranspiration (ET), corrected for crop stress;

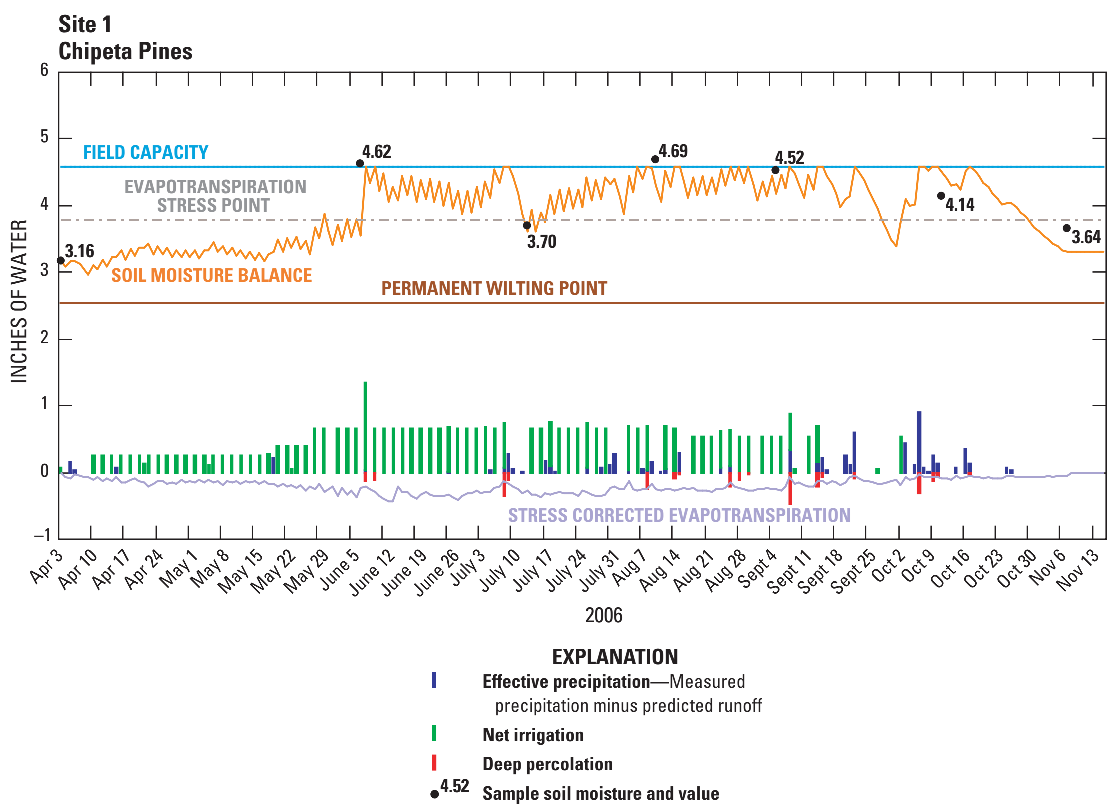


Figure 8. Soil-moisture balance for bluegrass on 1/4-acre residential lot site 1, Grand Valley, western Colorado.

- Red vertical bars indicate the deep percolation;
- Black dots with values indicate the measured soil moisture from core samples;
- Blue horizontal trace indicates the field capacity constant;
- Grey dashed trace indicates the evapotranspiration stress point constant;
- Brown horizontal trace indicates the permanent wilting point constant.

The soil-moisture balance (orange trace) is approximately fitted to the monthly soil-moisture values (black dots). This fit is affected by choices for field capacity, permanent wilting point, ET stress parameters, and particularly by irrigation efficiency. These parameters are discussed below.

Physics of the Daily Soil-Moisture Balance Calculation Technique

The daily soil-moisture balance spreadsheet calculation technique (equations 2–6 for this report) included a number of features to optimize the model to fit the physical system of an irrigated lawn. These features included:

- Correction of precipitation for estimated runoff as a function of rainfall intensity, soil type, and slope;
- Correction of irrigation-water application to account for losses due to leakage, evaporation, overspray, and runoff;
- Correction of evapotranspiration for crop stress and soil stress effects (already discussed);
- Calibration of soil-moisture balances by using gravimetric soil-moisture samples; and
- Adjustment (at some sites) of soil physics parameters (field capacity and wilting point) to better match field results.

The soil-moisture balance calculation technique input parameters are discussed below and are listed by site in table 5.

Soil Type

Soil type for each site determines the field capacity and wilting point (Duke, 1991). Soil types were determined graphically using the National Cooperative Soil Survey (NCSS) Web Soil Survey Web site (U.S. Department of Agriculture, 2007). Where two soil types occurred at a site, the proportions of each were determined and used to determine field capacity and wilting point for the site. The soil types provided by NCSS are for natural, undisturbed soil samples. Residential soil is typically disturbed by the construction process (wheel compression, backfilling, or mixing with gravel, sand, and construction debris), and further by soil amendments and changes made by the homeowner. Published soil types were used for the study sites, as field measurement of soil type was not practical. Some empirical refinements of soil physics parameters were made, as discussed herein.

Table 5. Soil-moisture balance model parameters for sites that use daily calculations.

[Field capacity, saturated water-holding capacity of soil; permanent wilting point, point at which no water is available for evapotranspiration; irrigation efficiency, empirically determined efficiency of irrigation-water application; %, percent; basal crop coefficient, starting crop coefficient for FAO-56 Penman-Monteith dual crop coefficient calculations; exposed fraction of soil, % of soil without vegetation; readily available water, amount of water that plant can readily use for evapotranspiration; readily evaporable water, amount of water that soil can readily lose in evapotranspiration]

Site number	Vegetation	Soil type	Field capacity (inches)	Permanent wilting point (inches)	Irrigation efficiency (%)	Basal crop coefficient (%)	Exposed fraction of soil (%)	Readily available water/readily evaporable water (%/%)	Crop height (inches)	Measured bulk density (grams per cubic centimeter)
1	Bluegrass	Loam	4.59	2.54	75	90	5	40/40	4	1.46
2	Bluegrass	Clay loam	4.59	2.54	75	90	5	40/40	4	1.55
6	Bluegrass	Loam	4.59	2.54	75	90	5	40/40	4	1.70
7W	Orchard grass	Clay loam	4.59	2.54	70	90	50	60/60	12	1.57
7E	Orchard grass	Clay loam	4.59	2.54	70	90	50	60/60	12	1.57
8	Bluegrass	Loam	4.59	2.54	75	90	5	40/40	4	1.49
9	Bluegrass	Clay loam	4.59	2.54	90	90	5	40/40	4	1.58
10	Native	Clay loam	4.59	0.50	75	90	20	40/40	4	1.65
11	Bluegrass	Clay loam	4.59	2.54	65	90	5	40/40	4	1.46
12	Bluegrass	Loam	4.59	2.54	90	90	5	40/40	4	1.57
13	Bluegrass	Clay loam	4.59	2.54	75	90	5	40/40	4	1.55
14	Bluegrass	Clay loam	4.59	2.54	75	90	5	40/40	4	1.46
15	Orchard grass	Loam	4.59	2.54	70	90	50	60/60	12	1.55
16	Orchard grass	Clay loam	4.59	2.54	70	90	50	60/60	12	1.55
17	Orchard grass	Clay loam	4.59	1.00	75	90	5	40/40	4	1.56
18	Bluegrass	Clay loam	4.59	2.54	70	90	5	40/40	4	1.65
21	Bluegrass	Clay loam	4.59	2.54	50	90	5	40/40	4	1.55
22	Bluegrass	Loam	4.59	2.54	55	90	5	40/40	4	1.57

Bulk density is a direct multiplier in the gravimetric soil-moisture calculation, making accurate bulk density values essential to determining soil moisture. The study determined bulk density by direct soil sampling at each site. These measured bulk densities typically were slightly higher than the published values for the soil types (Duke, 1991). Measured bulk densities for the study sites are given in table 5.

Field Capacity Corrections

The field capacity (FC) value, in inches, for each site, is shown in table 5. Published values for field capacity are based on soil types and are determined by a broad range of conditions (Duke, 1991). It is possible that the published FC reference value for a soil type does not precisely match the actual conditions at a given site with a matching soil type. The original researchers who defined FC commented that "field capacity is affected by so many factors that, precisely, it is not a constant (for a particular soil), yet it does serve as a practical measure of soil water-holding capacity" (Veihmeyer and Hendrickson, 1949). In this study, it was observed from the soil-moisture balance graphs that for sites with loam soils, an FC of 4.11 inches was systematically too low to explain the gravimetrically measured soil-moisture values at those sites. By arbitrarily raising the FC to that of clay loam (4.59 inches), the calculated soil-moisture balance more closely matched the gravimetrically measured values. Possible explanations for this effect are: (1) there is inaccuracy in the soil typing for those sites, and(or) the site is on an unmapped soil inclusion; or (2) the soil has been altered during construction and by the homeowner with soil amendments to improve turf quality and no longer performs like the native soil type (Frank Riggle, Natural Resources Conservation Service, written commun., 2007).

Considering the first of these possible explanations, within each soil-mapping unit there are areas of similar and(or) dissimilar soils called inclusions. These inclusions are usually described in the written soil survey narrative but are too small to show on maps. The soil type at an individual site may be different from the published type due to mapping or description errors, or the site may be located in a map unit inclusion (Frank Riggle, written commun., 2007).

The second possibility, changes to the native soil characteristics, would seem to be the most likely explanation. Fine-grained soils have larger field capacities than coarse-grained (sandy) soils. Thus, more water is available for actual ET from fine soils than coarse soils (Ritter, 2006). As discussed above, the bulk densities for most sites were higher than published values, which would be expected for soils with more fine grains.

Permanent Wilting Point Corrections

The permanent wilting point (PWP) was determined by the soil type at each site (table 5) from published values (Duke, 1991). In two cases, for orchard grass and for native plants (sites 17 and 10, respectively), the published PWP values did not allow the calculated soil-moisture balance to fall as low as the measured soil moistures were indicating. It was found that lowering the PWP allowed the calculated soil moisture to match closely the measured soil-moisture values. It is probable that for orchard grass and native plants, the root depth extends deeper than 12 inches, and thus the soil moisture in the top 12 inches of soil does not accurately reflect the moisture conditions that are available to the lower portion of the plant roots. This would imply that the PWP of the crop is not as quickly reached as for turf grass, whose roots are often only a few inches in depth.

Irrigation Efficiency

GIS was used to determine turf area (in square feet) for each site using 2001 to 2005 aerial photographs provided by Mesa County (Mesa County, Colo., 2005). Selected details were visually checked in the field for each site. Sprinkler overspray onto sidewalks and driveways was quantified one time for each site. The area of overspray was calculated and was used as a correction to the total irrigated area for the site. This had the effect of reducing the amount of water applied to the turf areas. Runoff into curbs and ditches also was observed one time for each site, but these values were considered to be included in the general number for irrigation efficiency. There was substantial overspray at a few sites, but relatively little runoff was observed at any of the sites.

Irrigation efficiency is the fraction of irrigation water available at the input to the irrigation system that actually ends up being applied to the crop and soil. It factors in bulk corrections to account for leakage in the pipes, wind losses, runoff, overspray, and crop canopy evaporation. Selection of different values of assumed irrigation efficiency has a striking effect on the calculated soil-moisture balance. Typical published irrigation efficiency values for agricultural sprinkler irrigation range from 50 to 90 percent (Howell, 2003); however, no published irrigation efficiencies for residential irrigation systems were found. A University of Florida residential irrigation researcher suggested residential irrigation efficiencies ranging from 50 to 90 percent, with 75 percent as a starting point, would be appropriate (Michael Dukes, University of Florida, Gainesville, written commun., 2006).

By comparing the calculated soil-moisture values on the days that the monthly measured soil-moisture samples were collected in 2006, the irrigation efficiency percentages were increased or decreased to achieve the best overall visual fit of the calculated soil-moisture curve to the measured monthly soil-moisture values. Because the irrigation efficiency percentage is applied linearly to each daily soil-moisture calculation, it was not possible to fit the curve to every measured soil-moisture value. Some measured soil-moisture values remained outliers to the calculated soil-moisture curve, probably due to unknown inadequacies of the daily soil-moisture balance model or local anomalies of measured soil moisture. Table 5 lists the derived irrigation efficiency for each site. Irrigation efficiency values of 70 or 75 percent were appropriate at 13 of the 18 residential study sites, with the other 5 sites (9, 11, 12, 21, and 22) requiring 90, 65, 90, 50, and 55 percent, respectively. An examination of the characteristics of these five sites (table 2) does not yield any obvious reasons that explain their atypical derived irrigation efficiencies. Three of the sites are 1/4-acre lots with bluegrass, and the other two sites are 5-acre estates with bluegrass. All five sites used a mixture of pop-up spray heads and impulse heads. One site has been in existence for approximately 20 years, with the other four sites being under 5 years of age. It was not possible at any of the sites to judge the conditions of the pipes to determine if leaks were occurring.

Evapotranspiration Stress Correction Parameters

The ET stress correction parameters that are required for the FAO-56 Penman-Monteith ET calculation method were entered into the daily soil-moisture balance model once for each site. These parameters include the basal crop coefficient, percentage of readily available water, percentage of readily evaporable water, exposed fraction of soil, and crop height in inches. Table 5 shows the ET stress parameters selected for each site. The daily meteorology parameters for stress correction were entered in the model from the CSU COAGMET weather station data closest to each site.

Whole Subdivision Irrigation-Water Application and Deep Percolation

The total irrigated area in each of the three subdivisions was determined graphically, lot by lot, from color and infrared 2001 to 2005 aerial photographs provided by Mesa County. The total subdivision areas were determined using the aerial photographs in GIS, and the percentage of irrigated land in each subdivision was calculated. The mean values of irrigation water applied and deep percolation were determined for bluegrass-only and all-vegetation type study sites in each subdivision. Mean site values were multiplied by total irrigated area in each subdivision to provide an estimate of the volume of irrigation water applied and deep percolation for each whole subdivision.

Holding-Pond Water Balance

Topographic Surveys

To calculate the seepage of pond water over time, it was necessary to create an area-capacity curve to relate the pond-water level (stage) to pond volume. The bathymetry of two of the ponds (Quail Run and Chipeta Pines) was surveyed while dry using total station surveying equipment (Anderson and Mikhail, 1998). The Paradise Hills pond was surveyed while full of water using acoustic Doppler depth-sounding equipment in conjunction with a high-accuracy GPS receiver (Wilson and Richards, 2006). Using the bathymetry data, a 3D model of each pond was created in ARCMap (Environmental Systems Research, Inc., 1999–2005). Using ARCMap 3D Analyst, the 3D model was then divided into 0.1-meter (0.33-ft) horizontal surfaces, and the volume below each slice was calculated. These volumes were then plotted in Microsoft Excel to fit a 3d-order polynomial area-capacity equation of stage in relation to volume for each pond. The three pond area-capacity equations are:

Quail Run Pond:

$$V = -69.867 \times S^3 + 1912.2 \times S^2 - 1448.3 \times S + 231.39 \quad (R^2 = 0.9999), \tag{7}$$

Chipeta Pines Pond:

$$V = -39.914 \times S^3 + 1153.9 \times S^2 - 500.65 \times S + 74.649 \quad (R^2 = 0.9998), \tag{8}$$

Paradise Hills Pond:

$$V = -842.9 \times S^3 + 11968 \times S^2 - 8603.8 \times S + 727.71 \quad (R^2 = 0.9999), \tag{9}$$

where

V is pond volume in cubic feet,

S is pond stage in feet,

and

R^2 is correlation coefficient, between 0 and 1, with 1 being the best fit of the equation to the data.

Stage change during the observation period was converted to volume using the area-capacity curve. Seepage from the unlined pond was then estimated from the change in volume, accounting for pan evaporation and effective precipitation. Pond stage was observed for about 3 weeks in November, from the time irrigation water was cut off until freezing temperatures halted the ability to collect pan evaporation data.

Water Balance Calculation

The pond-water level (stage) was monitored after the irrigation water inflow to the pond was stopped at the end of the irrigation season; thus, irrigation water inflow equals zero in the water balance equation. In addition, pumping from the pond was discontinued, so there were only two components for outflow: evaporation and seepage. Because it was assumed that all the ponds in the study were perched, ground-water inflow could be ignored. Evaporation was measured using an evaporation pan. Seepage from the pond is calculated:

$$seepage_{pond} = pond\ stage_{starting} - pond\ stage_{ending} - total\ evaporation - precipitation_{daily} \tag{10}$$

where

$seepage_{pond}$ is the water lost from the pond during observation period (inches),

$pond\ stage_{starting}$ is the level of water at start of observation period (inches),

$pond\ stage_{ending}$ is the level of water at end of observation period (inches),

$total\ evaporation$ is the pan evaporation during observation period (inches),

and

$precipitation_{daily}$ is the measured total daily precipitation (inches).

Seepage for an entire irrigation season was estimated by multiplying average daily seepage by the total number of season days.

Salt-Loading Calculation

Salt loading in the Colorado River occurs when irrigation water percolates below the root zone, or seeps from a pond, and eventually reaches the river with salt that has leached from the Mancos Shale soils in the Grand Valley. Salt loading is expressed in tons of salt per acre-foot of deep percolation, and is calculated using a standard "loading factor" of 4.1 tons per acre-foot of deep percolation for the Grand Valley (Hedlund, 1994). The volume of deep percolation from a site is assumed by NRCS to be decreased by a "standard average return flow reduction." This reduction corrects for deep percolation and seepage that is picked up and reused by lower lying irrigation systems, intercepted by deep rooted plants such as shrubs and trees, used by phreatophytic plants, evaporated in irrigation-induced wetlands, or used by vegetation along the irrigation drains. The standard average return flow reduction for the Grand Valley is 50 percent, a value administratively set by the NRCS for Utah, Wyoming, and Colorado (Frank Riggle, oral commun., 2007). This means that only 50 percent of the deep percolation at a site is assumed to contribute to salt loading at the river.

The salt loading equation is thus:

$$\textit{salt loading} = \textit{salt loading rate} \times \textit{deep percolation} \times \textit{return flow factor}, \qquad (11)$$

where

salt loading is the quantity of salt reaching the Colorado River (tons),

salt loading rate is the standard leaching rate, 4.1 tons per acre-foot for Grand Valley,

deep percolation is the irrigation water reaching the groundwater table, equivalent to seepage for a pond (acre-feet),

and

return flow factor is the amount of water that is subsequently re-used for irrigation or used by vegetation (50 percent).

Sources of Measurement Calculation Errors

Principal sources of error in estimates of factors used to calculate deep percolation are shown in table 6. The types of errors fall into two categories: (1) inherent errors of instrumentation measurements; and (2) assumed irrigation application efficiency values.

Instrumentation Measurement Errors

The manufacturer's specifications for accuracy of the various data collection instruments are shown in table 6. Because the instruments are relatively accurate, compared with other potential sources of error in the study, it was determined that instrument error could be disregarded for data analysis purposes.

Irrigation Application Efficiency Errors

The derivation for irrigation efficiency at each site was discussed in the Daily Soil-Moisture Balance section. The comparability or "fit" of the calculated soil-moisture curve to the measured soil-moisture core samples is very sensitive to the value selected for irrigation efficiency. As such, the selected value for irrigation efficiency directly affects the final deep percolation calculations. Because it was not possible to quantify irrigation efficiency, the irrigation efficiency value was adjusted to achieve the best visual fit of the soil-moisture balance curve to measured soil-moisture values for each site. Irrigation efficiency values selected for each site are shown in table 5.

Handwritten Event Log Errors

In 2006, homeowners kept a handwritten irrigation event log as a backup data source in case of data logger malfunctions. An indirect benefit of this backup data set was the ability to calculate an error rate for the 2006 handwritten logs that could be used to estimate similar errors for 2005 when data loggers were not used to automate logging of irrigation events. The monthly total of irrigation minutes was obtained from the sprinkler-timer data logger for each residential site. These totals were compared with the total number of irrigation minutes each homeowner recorded in his log. If the homeowner underreported irrigation minutes, this was considered a negative error, and overreported minutes by the homeowner was a positive error. A percentage error was calculated for the eight residential sites in 2006 (fig. 9).

In general, most homeowners reported irrigation records accurately, but several homeowners in 2006 tended to underreport irrigation events during the first 3 months of the season. It can be seen in figure 9 that most of the errors occurred in the beginning of the irrigation season, probably due to a learning curve for the homeowners in keeping the records. It was decided that this was an acceptable error rate due to the relative low application of water in the early months of the season, with little or no resulting deep percolation. No corrections were made to the 2005 irrigation event logs, although some underreporting could reasonably be assumed to have occurred.

Natural Resources Conservation Service Monitoring and Evaluation Data

The NRCS M&E deep percolation data for 1985 through 2002 were available in hard copy form (about 1,000 pages of printed annual reports). There were no NRCS M&E sites monitored from 1996 through 1998. Table 7 summarizes the NRCS M&E data for all crop-type sites and for alfalfa-only sites. Many of the NRCS M&E sites were monitored for multiple successive years, and each year of data for a site is considered to be a separate record for analysis.

Table 6. Principal sources of error in estimates of factors used to calculate deep percolation in urban study data.

[±, plus or minus; %, percent]

Data system	Type of error	Source of error estimate	Error magnitude	Effect on deep percolation results
Sprinkler-timer data logger (2006 only)	Starting and ending time of event	Data scan rate is every 60 seconds	1 to 59 seconds maximum per event start or stop time	Small
GE Panametrics flow meter model PT878	Measurement	Published specification of PT878 flow meter accuracy[1]	[2]±2%	Small
Spectrum Technologies Weather Station	Measurement	Published specification for Weather Station tipping bucket rain collector[3]	±2%	Small
Irrigation application efficiency	Qualitative estimates	Uncertainty in amount of leaks, wind effects, canopy evaporation, runoff, overspray	Unknown	Large

[1]GE Panametrics flow meter specifications accessed June 11, 2007, at *http://www.gesensing.com/products/pt878gc.htm?bc=bc_panametrics*

[2] GE Panametrics flow meter requires a pipe full of liquid. No flow readings are possible unless the pipe is full.

[3]Spectrum Technologies Weather Station specifications accessed June 11, 2007, at *http://www.specmeters.com/WatchDog_IPM_Weather_Stations/Plant_Disease_Weather_Station.html*

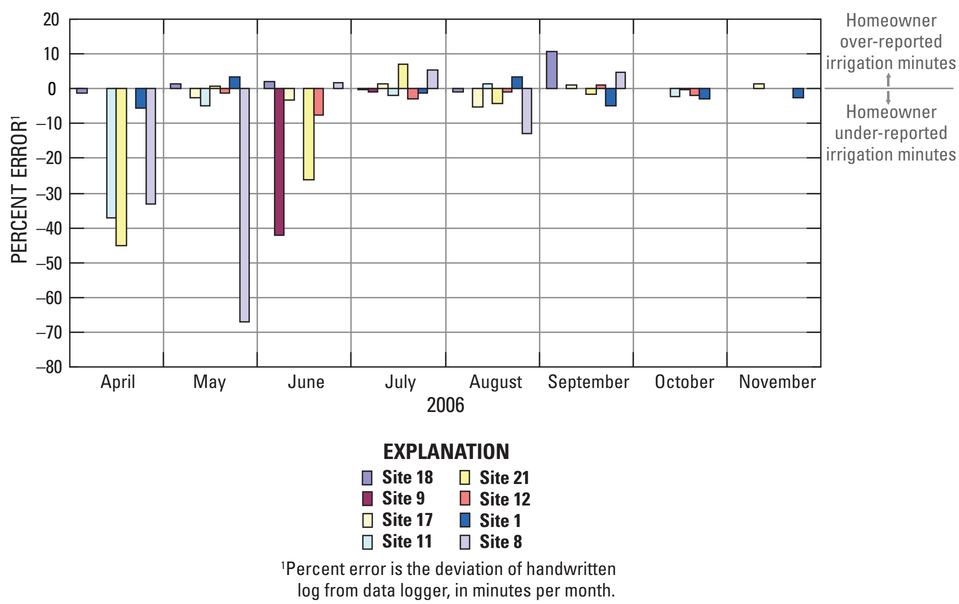


Figure 9. Comparison of handwritten subdivision irrigation event logs to automated logger data for eight sites, 2006 season.

It was decided to include only NRCS M&E alfalfa-crop sites in the comparison with current study sites. Alfalfa was recommended as the best agricultural crop for comparison by the NRCS (Jim Currier, Natural Resources Conservation Service District Conservationist, oral commun., 2006) because alfalfa has been a widely grown crop in the Grand Valley and commonly is the agricultural crop that is converted to urban residential land use. Alfalfa also represents a substantial portion of the NRCS M&E data set and is one of the standard reference crops for ET calculations. In addition, 20 unique site locations (67 irrigation seasons of data) for alfalfa crops were included in the NRCS M&E data, representing a large data set for analysis. The number of sites studied per year ranged from 4 to 11. The longest period of study for any single site was 10 years. The alfalfa-crop sites included eight types of irrigation methods. Irrigated alfalfa-crop field size ranged from 2 to 54 acres, with a mean size of 23.8 acres.

To preserve landowner anonymity, precise NRCS M&E site locations were not recorded, but all alfalfa-crop sites included in this analysis were located in the Grand Valley. Deep percolation results from the NRCS M&E were summarized by irrigation method, crop type, and field size. Ten annual reports listed individual irrigation event data per site, while the other five listed only annual totals for irrigation events per site.

Table 7. Summary of Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) sites and seasons for all crop types and for alfalfa crops, 1985–2002.

[ET, evapotranspiration; -, no data applicable]

NRCS M&E year	Total number of all crop type sites studied	Total number of alfalfa-crop sites studied	Annual/ per irrigation event ET data available	Annual/ per irrigation event data recorded
1985	[1]15	[1]4	Yes	Annual
1986	16	4	Yes	Annual
1987	16	4	Yes	Annual
1988	18	6	Yes	Per event
1989	19	9	Yes	Per event
1990	25	7	Yes	Per event
1991	23	9	Yes	Per event
1992	24	11	Yes	Per event
1993	21	7	Yes	Per event
1994	12	5	Yes	Annual
1995	7	1	Yes	Annual
1996	0	-	-	-
1997	0	-	-	-
1998	0	-	-	-
1999	[1]11	[1]0	Yes	Per event
2000	[1]6	[1]0	No	Per event
2001	[1]2	[1]0	No	Per event
2002	2	[1]0	No	Per event
Totals	**217**	**67**		

[1]Some sites omitted due to missing or invalid data.

Comparison between Natural Resources Conservation Service Monitoring and Evaluation Data and Urban Study Data

Comparisons between the two studies included annual water application and deep percolation rates. Grand Valley alfalfa-crop sites (20 sites, 67 irrigation seasons of data) were extracted from the NRCS M&E data for comparison. Data for several NRCS M&E alfalfa-crop sites were excluded because of erroneous or missing data.

Effects of Conversion of Agricultural Land to Urban Land on Deep Percolation of Irrigation Water

Residential Lots, Estates, and Parks Results

A data summary for the urban homes and parks for the 2005 season is listed in table 8. The 2006 season summary is listed in table 9.

Example Soil-Moisture Balance Charts

Several soil-moisture balance charts are shown to illustrate typical results of calculations of deep percolation for the study. A complete set of soil-moisture balance charts for the study is included in Appendix 1.

2005 Soil-Moisture Charts

Figure 10 is the 2005 soil-moisture chart for site 2, a 1/4-acre residential lot. The vegetation is bluegrass. Cumulative deep percolation for the season was 13.7 inches (table 8). Two soil-moisture samples were collected in 2005, in May and in September. This homeowner irrigates on a regular basis, with a day or two between each application. The soil-moisture balance exceeds field capacity starting in July and continuing in August, creating deep percolation. Most irrigation events during July, August, and September create deep percolation because of excessive irrigation application. The early season deep percolation in May could be attributed to the assumption that initial soil moisture was at field capacity. In the second week of July, the irrigation quantity was increased from about 0.5 inch per application to about 0.8 inch, leading to deep percolation at almost every irrigation application. There is a good fit of the calculated soil-moisture balance curve to the two measured soil-moisture core sample values.

Figure 11 is the 2005 soil-moisture chart for site 9, a 5-acre estate. The vegetation is bluegrass. Cumulative deep percolation for the season was 2.4 inches (table 8). This homeowner managed water application carefully, generally keeping the moisture balance around the ET stress point. Very little deep percolation occurred except at the beginning and end of the season. The early season deep percolation in May is attributable to the assumption of initial soil moisture being at field capacity, and the late-season deep percolation was caused by a combination of reduced ET and continued irrigation. There is a good fit of the calculated soil-moisture balance to the two measured soil-moisture core sample values.

Figure 12 is the 2005 soil-moisture chart for site 6, a subdivision commons park. The vegetation is bluegrass. Cumulative deep percolation for the season was 0.1 inch (table 8). The irrigation application rate was relatively low at about 0.3 inch every 2 or 3 days, keeping the soil moisture well below the readily available water level most of the season. Only 0.1 inch of deep percolation occurred at this site. There is a generally good fit of the calculated soil-moisture balance to the measured soil-moisture core sample values.

2006 Soil-Moisture Charts

Figure 13 is the 2006 soil-moisture chart for site 8, a 1/4-acre residential lot. The vegetation is bluegrass. Cumulative deep percolation for the season was 0.8 inch (table 9). The homeowner typically irrigated every second or third day

Table 8. Summary of data and results of deep percolation calculations for 2005 irrigation season for residential lots, estates, and urban parks.

[Net irrigation applied, irrigation applied multiplied by irrigation efficiency; stress corrected ET, evapotranspiration corrected for crop stress; effective precipitation, measured precipitation minus predicted runoff]

Site number (fig. 1, table 1)	Site type	Vegetation	Irrigated area (acres)	Net irrigation applied (inches)	Stress corrected ET (inches)	Effective precipitation (inches)	Total deep percolation (inches)	Total deep percolation (acre-feet)
1	¼-acre residential lot	Bluegrass	0.1	45.1	37.5	2.7	10.2	0.10
2	¼-acre residential lot	Bluegrass	0.1	43.8	35.6	5.5	13.7	0.14
6	Commons park	Bluegrass	0.5	22.5	25.3	2.7	0.1	0.00
8	¼-acre residential lot	Bluegrass	0.1	17.2	21.4	2.7	0.1	0.00
9	5-acre estate lot	Bluegrass	1.1	31.4	33.4	4.5	2.4	0.23
10	5-acre estate lot	Native plants	0.6	5.0	12.9	4.5	0.0	0.00
11	5-acre estate lot	Bluegrass	0.1	26.7	32.1	4.5	0.2	0.00
12	¼-acre residential lot	Bluegrass	0.1	25.5	30.9	5.0	0.0	0.00
13	¼-acre residential lot	Bluegrass	0.1	36.0	40.8	5.5	1.4	0.02
14	5-acre estate lot	Bluegrass	1.0	28.9	32.7	5.2	2.9	0.24
18	5-acre estate lot	Bluegrass	0.8	39.7	41.2	5.2	3.5	0.24
22	¼-acre residential lot	Bluegrass	0.1	27.6	31.0	5.0	1.2	0.01
Mean			**0.4**	**29.1**	**31.2**	**4.4**	**3.0**	**0.08**

Table 9. Summary of data and results of deep percolation calculations for 2006 irrigation season for residential lots, estates, and urban parks.

[Net irrigation applied, irrigation applied multiplied by irrigation efficiency; stress corrected ET, evapotranspiration corrected for crop stress; effective precipitation, measured precipitation minus predicted runoff]

Site number (fig. 1, table 1)	Site type	Vegetation	Irrigated area (acres)	Net irrigation applied (inches)	Stress corrected ET (inches)	Effective precipitation (inches)	Total deep percolation (inches)	Total deep percolation (acre-feet)
1	1/4-acre residential lot	Bluegrass	0.1	38.5	42.6	7.1	2.8	0.03
6	Commons park	Bluegrass	0.5	25.1	47.1	7.1	0.8	0.03
8	1/4-acre residential lot	Bluegrass	0.1	26.6	32.2	7.1	0.8	0.00
9	5-acre estate lot	Bluegrass	1.1	40.1	43.1	7.0	3.1	0.29
10	5-acre estate lot	Native plants	0.6	4.2	12.1	7.0	0.0	0.00
11	5-acre estate lot	Bluegrass	0.1	37.0	38.4	7.0	5.2	0.06
12	1/4-acre residential lot	Bluegrass	0.1	31.0	38.1	7.2	0.2	0.00
17	5-acre estate lot	Orchard grass	1.7	29.8	34.6	7.0	1.3	0.19
18	5-acre estate lot	Bluegrass	0.8	43.1	44.0	7.0	5.4	0.37
21	1/4-acre residential lot	Bluegrass	0.1	28.9	35.4	6.8	0.2	0.00
Mean			**0.5**	**30.4**	**36.8**	**7.0**	**2.0**	**0.10**

and kept the soil-moisture balance generally just below the ET stress point. The only calculated deep percolation occurred in October when almost 1 inch of effective precipitation fell in one day, as measured at the local subdivision weather station. The homeowner suspended irrigation during this wet period, so all the deep percolation during that time was attributable to rainfall. There is a generally good fit of the calculated soil-moisture balance to the measured soil-moisture core sample values, with the exception of the last sample collected in October. At that time, the calculated soil moisture was higher than the actual soil moisture, likely due to the precipitation that fell in early October. The most probable explanation for this is that precipitation runoff was understated for this wet period, leading to calculated soil-moisture balances that were artificially high.

Figure 14 is the 2006 soil-moisture balance chart for site 18, a 5-acre estate. The vegetation is bluegrass. Cumulative deep percolation for the season was 5.4 inches (table 9). This homeowner applies approximately 0.3 inch of water nearly daily, resulting in a soil-moisture balance that stays well above the ET stress point after May. The soil-moisture balance exceeds field capacity frequently during July, August, September, and October, creating deep percolation on many days. The largest daily deep percolation occurrence coincided with the heavy

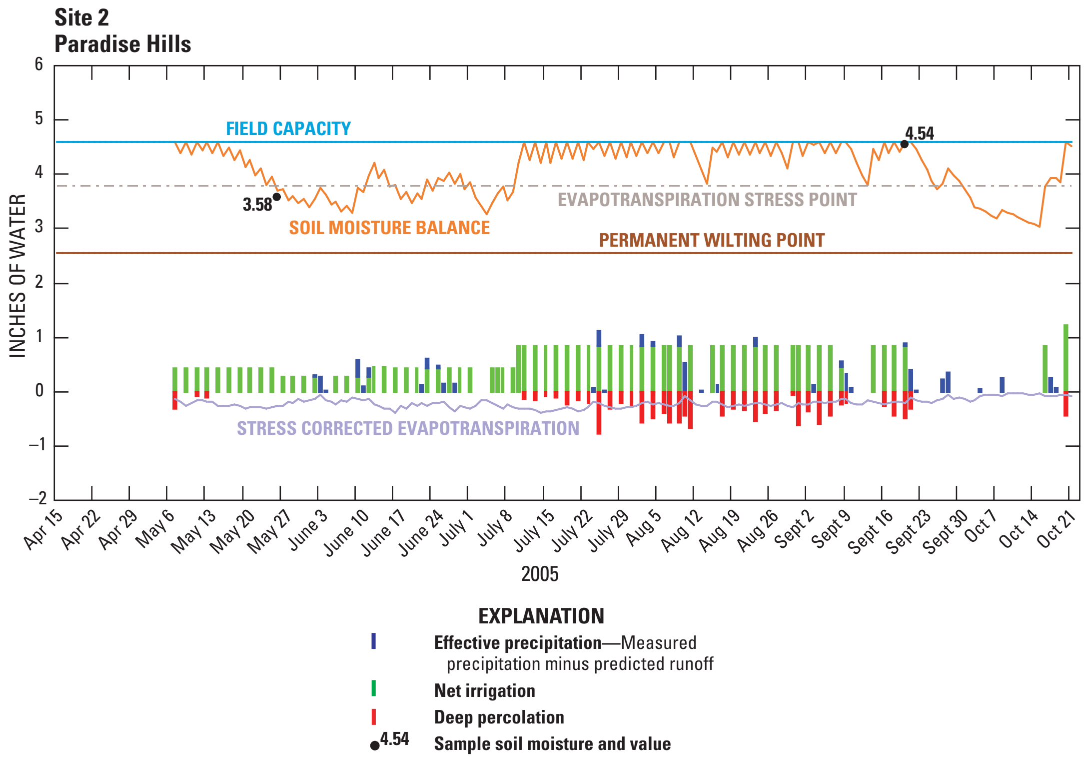


Figure 10. Soil-moisture balance for bluegrass on 1/4-acre residential lot site 2, Grand Valley, western Colorado.

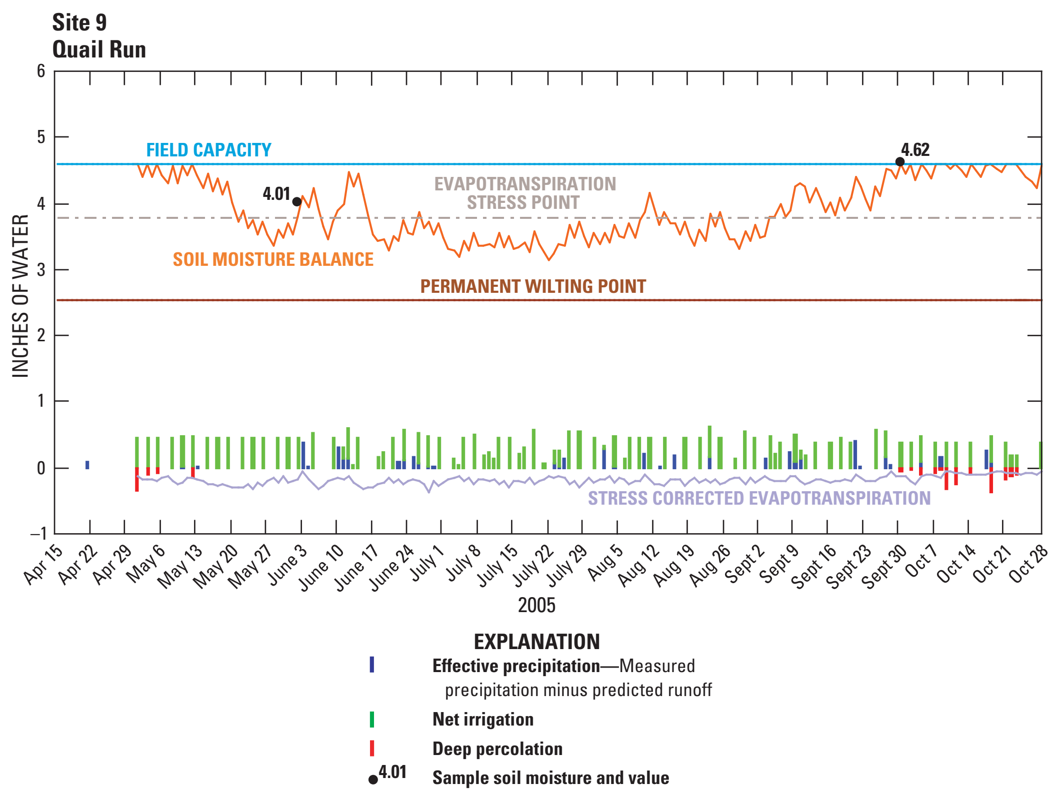


Figure 11. Soil-moisture balance for bluegrass on 5-acre estate site 9, Grand Valley, western Colorado.

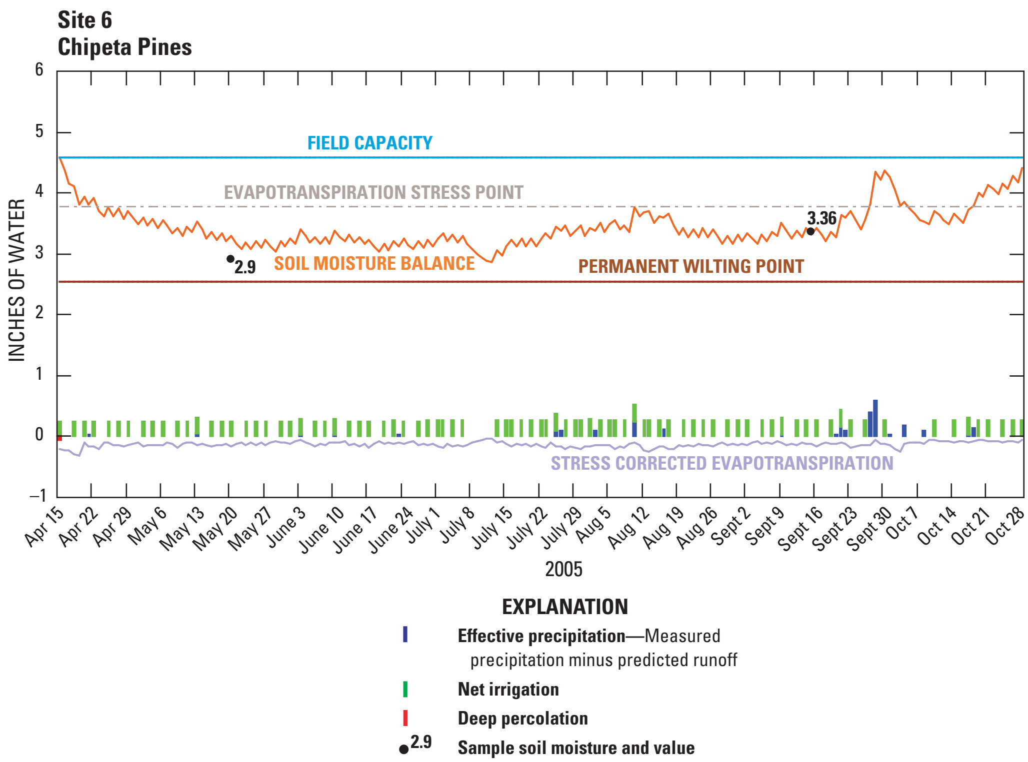


Figure 12. Soil-moisture balance for bluegrass on subdivision commons park site 6, Grand Valley, western Colorado.

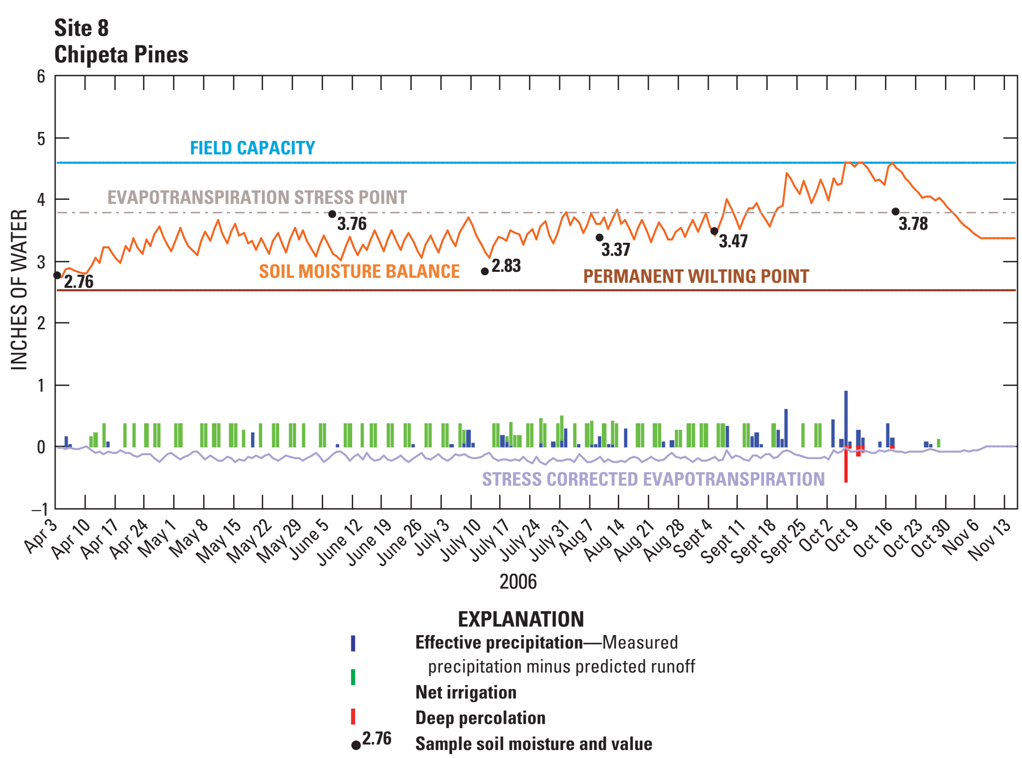


Figure 13. Soil-moisture balance for bluegrass on 1/4-acre residential site 8, Grand Valley, western Colorado.

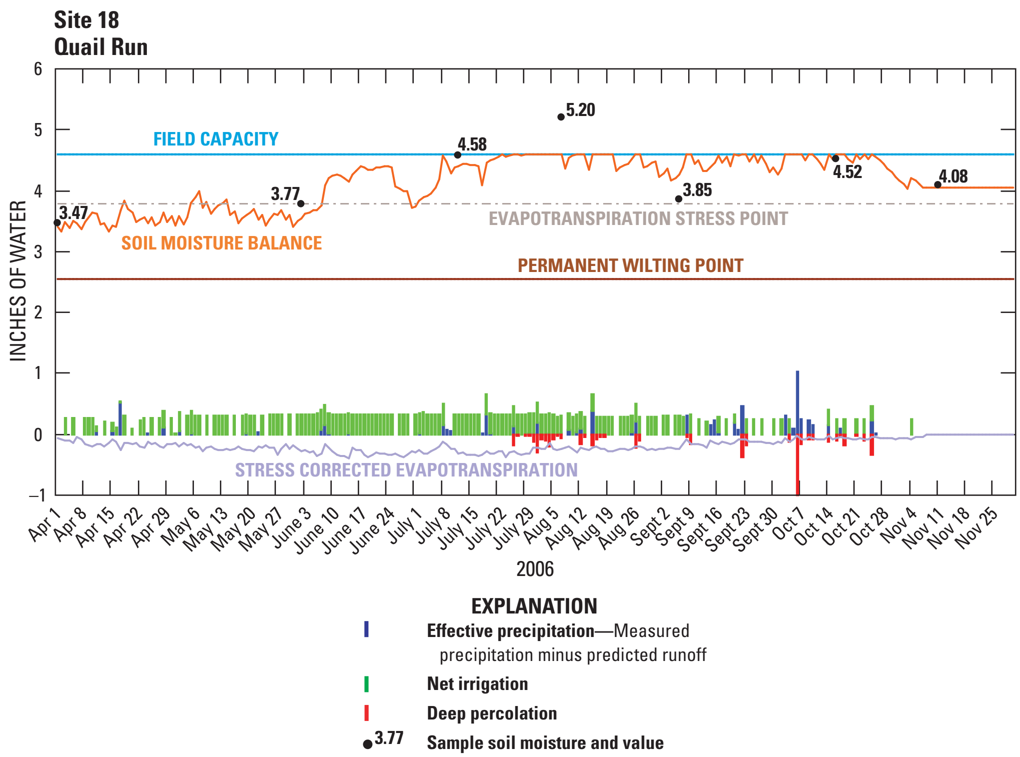


Figure 14. Soil-moisture balance for bluegrass on 5-acre estate site 18, Grand Valley, western Colorado.

precipitation the first week of October. There is a generally good fit of the calculated soil-moisture balance to the measured soil-moisture core sample values, with the exception of the early August soil sample, which is above field capacity. Because deep percolation had been occurring often for several weeks prior to that date, it is quite possible that the soil was saturated on the sampling day. Soil moisture of this magnitude is feasible on a temporary basis if the soil is saturated and has not returned to the equilibrium level of field capacity.

Figure 15 is the 2006 soil-moisture balance chart for site 10, a 5-acre estate. The vegetation is native plants. There was no deep percolation during the season. Irrigation application of about 0.2 inch occurred approximately weekly, resulting in no deep percolation. It should be noted that the PWP for this site was set to 0.50 inch to obtain the best visual fit of the calculated soil-moisture balance curve to the measured soil-moisture core sample values. The justification for this change in permanent wilting point is that native plants have deeper root systems and desert-adapted foliage and therefore are more tolerant of low soil moisture at the 0–12 inch depth zone sampled in this study than bluegrass.

Figure 16 is the 2006 soil-moisture balance chart for site 17, a 5-acre estate. The vegetation is orchard grass. Cumulative deep percolation for the season was 1.3 inches. Irrigation application of about 0.4 inch occurred approximately every 3 to 4 days until early June, resulting in no deep percolation. Then starting in June, daily irrigation was scheduled, with smaller amounts on several consecutive days punctuated with a larger amount (about 0.5 inch) every few days, again with no deep percolation occurring. The soil-moisture balance stays well under the ET stress point until the fall rains begin. The first deep percolation of the season occurred in the first week of October during several precipitation events that pushed soil moisture beyond field capacity. It should be noted that the PWP was lowered to 1.0 inch for this site. There is a generally good fit of the calculated soil-moisture balance to the measured soil-moisture core sample values, with the exception of the samples collected in September, October, and November. At those times, the calculated soil moisture was generally greater than the actual soil moisture, likely due to the periodic precipitation that fell starting in September and continuing through October. The most probable explanation for this difference is either: (1) precipitation runoff was understated for this wet period, leading to calculated soil-moisture balances that were artificially high; or (2) actual ET was greater than calculated during this period.

Urban Gated-Pipe Field Results

Figure 17 is the 2006 soil-moisture balance chart for site 15, a privately owned gated-pipe field. The vegetation is orchard grass. The irrigation events occurred about every 2 or 3 weeks. Each of the seven irrigation events applied water in sufficient quantity to result in a total of 12.0 inches of deep percolation (table 10).

At the two privately owned fields (sites 15 and 16) during the 2006 season, there were seven and eight irrigation events, respectively. At the CSU-operated field (sites 7W and 7E), there were five pairs of irrigation events for the 2006 season. The results for gated-pipe fields are shown in table 10. Sites 7W and

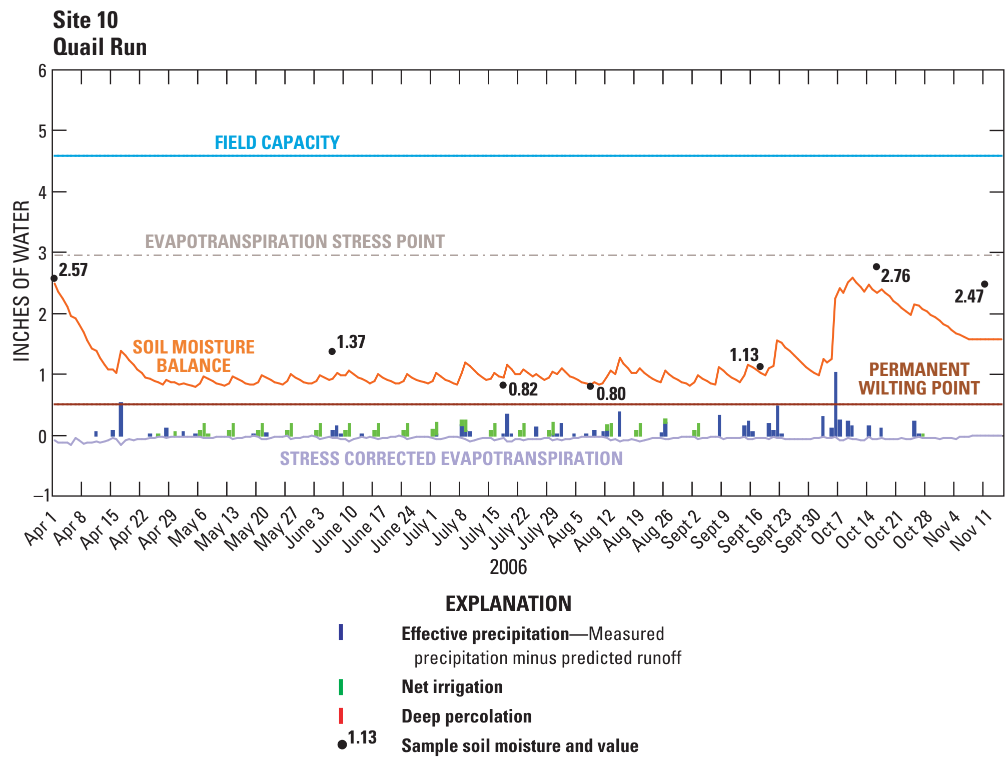


Figure 15. Soil-moisture balance for native plants on 5-acre estate site 10, Grand Valley, western Colorado.

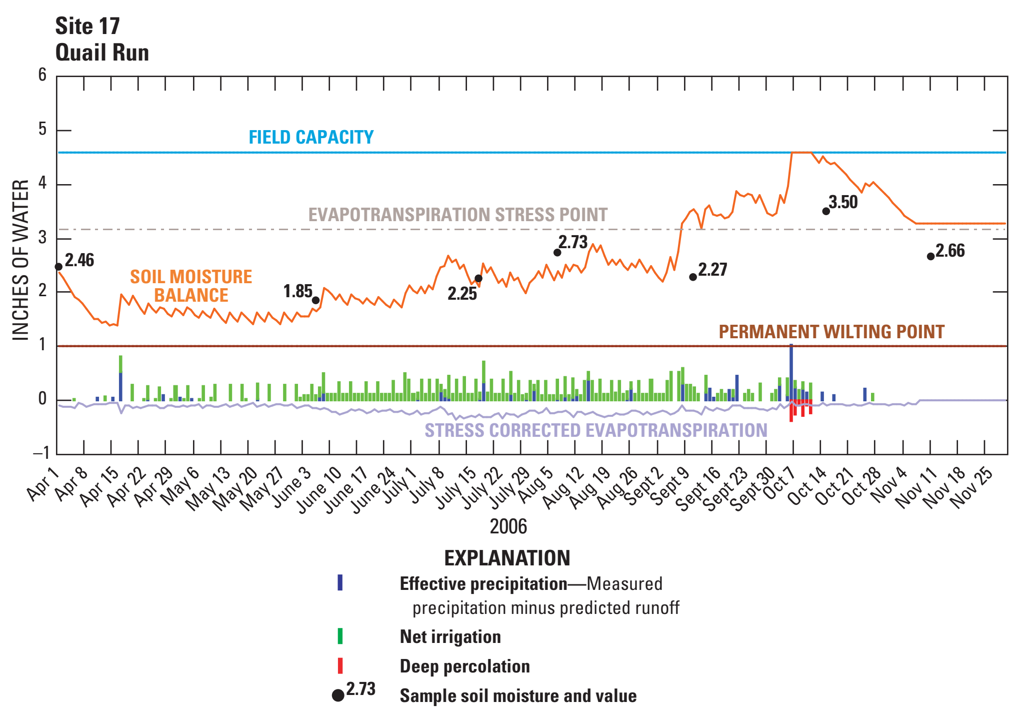


Figure 16. Soil-moisture balance for orchard grass on 5-acre estate site 17, Grand Valley, western Colorado.

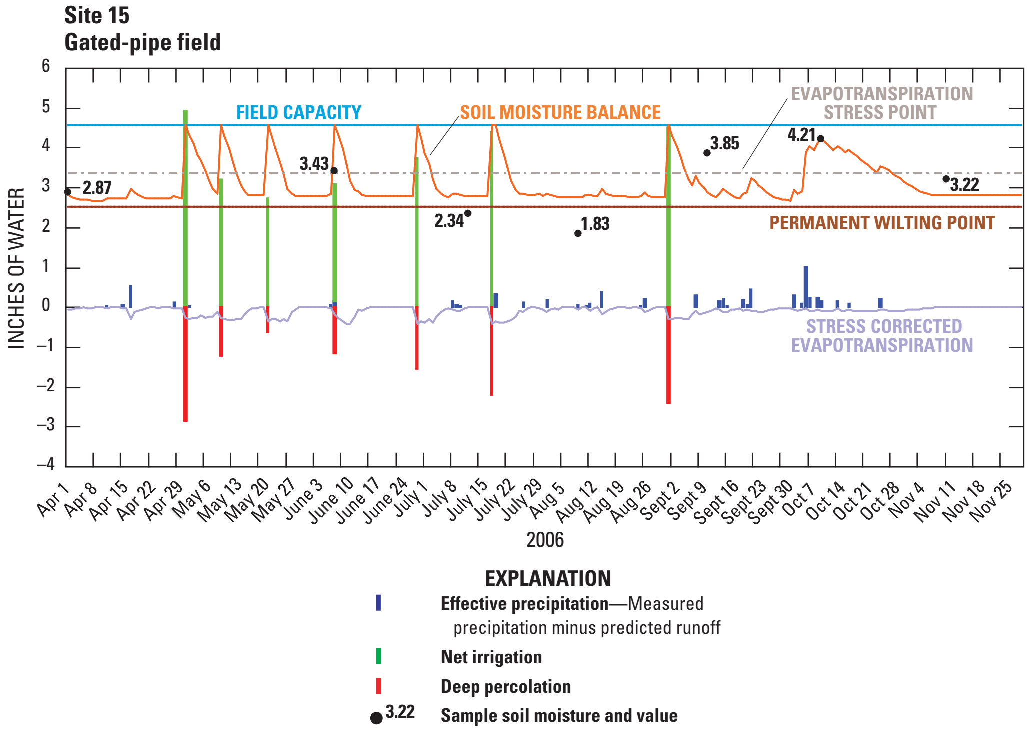


Figure 17. Soil-moisture balance for orchard grass on gated-pipe field site 15, Grand Valley, western Colorado.

Table 10. Summary of data and results of deep percolation calculations for 2006 irrigation season for gated-pipe fields.

[Net irrigation applied, irrigation applied multiplied by irrigation efficiency; stress corrected ET, evapotranspiration corrected for crop stress; effective precipitation, measured precipitation minus predicted runoff]

Site number	Site type	Vegetation	Number of irrigation events	Irrigated area (acres)	Net irrigation applied (inches)	Stress corrected ET (inches)	Effective precipitation (inches)	Total deep percolation (inches)	Total deep percolation (acre-feet)
7W	Gated-pipe field	Orchard grass	5	1.0	9.9	15.7	5.8	0.0	0.00
7E	Gated-pipe field	Orchard grass	5	1.0	8.8	14.6	5.8	0.0	0.00
15	Gated-pipe field	Orchard grass	7	1.0	26.4	21.5	7.0	12.0	0.95
16	Gated-pipe field	Orchard grass	8	2.1	35.8	22.9	7.0	20.1	3.57
Mean			**6.3**	**1.3**	**20.2**	**18.7**	**6.4**	**8.0**	**1.13**

7E had no cumulative deep percolation for the season, while sites 15 and 16 had 12.0 and 20.1 inches, respectively. The lack of deep percolation at sites 7W and 7E may be because the irrigation operator for the site is a professional agriculturist, whereas the owner/operator of sites 15 and 16 is not. The deep percolation results for sites 15 and 16 may be more indicative of urban gated-pipe fields that are operated as a hobby, although the sample sizes in this study are too small for statistical significance to be inferred from these results.

Analysis of Residential Sites, Parks, and Gated-Pipe Fields

For data analysis purposes, irrigation-water application and deep percolation results were combined in two ways: (1) bluegrass-only sites and (2) sites with all-vegetation types (bluegrass, orchard grass, and native plants). Bluegrass-only sites were separated for analysis because turf is the most common irrigated land cover associated with residential development; therefore, turf is the best measure of the effect of land-use conversion from agricultural to urban.

Bluegrass-Only Sites

Summary statistics for the irrigated areas of all bluegrass residential lots, estates, and urban parks are shown in table 11 for 19 irrigation seasons of data collected at 12 sites. Mean effective precipitation was 5.5 inches, the median was 5.5 inches, and the standard deviation was 1.6. Mean ET was 35.1 inches, median ET was 35.4 inches, and the standard deviation was 6.0. The mean value for irrigation water applied was 32.4 inches, while the median was 31.0 inches, with a standard deviation of 7.9. Mean deep percolation for bluegrass irrigation was 2.8 inches. Median deep percolation was 1.4 inches, and the standard deviation was 3.7. Summary statistics by site type for bluegrass-only sites are tabulated in table 12. Figure 18 shows a dot chart of the same data for deep percolation in inches by site type. The mean seasonal deep percolation was 3.1 inches and 3.2 inches for 1/4-acre lots and 5-acre estates, respectively (table 12). Figure 19 shows a dot chart of irrigation-water application in inches by site type. The park may have been more closely managed to conserve water than the residential lots. Water application was much less, ranging from about 23 to 25 inches as compared to about 17 to 45 inches for residential sites. In addition, deep percolation was low for the park (mean 0.4 inch).

Statistical Tests for Bluegrass-Only Sites

Two types of nonparametric statistical tests were used to determine if a study result could be explained by (1) another variable, or (2) by the groups into which the study result could be categorized. For example, the first type of test, Kendall's Tau, can indicate whether the amount of net irrigation applied explains the deep percolation results at a site. The second type of test, Kruskal-Wallis, can indicate whether the particular vegetation type at a site resulted in significantly different amounts of deep percolation. Kendall's Tau test involves calculating the correlation between two continuous variables and indicates a significant correlation when the 2-tailed p-value is less than 0.05. Kruskal-Wallis Test measures whether the medians of discrete groups of variables are

Table 11. Summary statistics for bluegrass-only vegetation on residential lots, estates, and urban parks.

[Effective precipitation, measured precipitation minus predicted runoff; evapotranspiration, evapotranspiration corrected for crop stress; irrigation applied, irrigation applied multiplied by irrigation efficiency]

Statistic	Effective precipitation (inches)	Evapotranspiration (inches)	Irrigation applied (inches)	Deep percolation (inches)
Minimum	2.7	21.4	17.2	0.0
25th percentile	4.8	31.6	26.7	0.2
Median	5.5	35.4	31.0	1.4
Mean	5.5	35.1	32.4	2.8
75th percentile	7.0	39.6	39.1	3.3
Maximum	7.2	44.0	45.1	13.7
Standard deviation	1.6	6.0	7.9	3.7

Table 12. Summary statistics by site type for bluegrass-only vegetation on residential lots, estates, and urban parks.

[Total irrigation seasons, sum of all irrigation seasons for all sites studied; net irrigation applied, irrigation applied multiplied by irrigation efficiency; stress corrected ET, evapotranspiration corrected for crop stress; effective precipitation, measured precipitation minus predicted runoff]

Site type/ (total irrigation seasons)	Statistic	Irrigated area (acres)	Net irrigation applied (inches)	Stress corrected ET (inches)	Effective precipitation (inches)	Deep percolation (inches)
1/4-acre residential lot (10)	Minimum	0.05	17.2	21.4	2.7	0.0
	25th percentile	0.05	26.9	31.3	5.0	0.2
	Median	0.08	29.9	35.5	5.5	1.0
	Mean	0.09	32.0	34.6	5.4	3.1
	75th percentile	0.12	37.9	38.0	7.0	2.4
	Maximum	0.14	45.1	42.6	7.2	13.7
	Standard deviation	0.04	8.8	6.1	1.7	4.8
5-acre Estate (7)	Minimum	0.14	26.7	32.1	4.5	0.2
	25th percentile	0.48	30.2	33.1	4.9	2.6
	Median	0.82	37.0	38.4	5.2	3.1
	Mean	0.74	35.3	37.9	5.8	3.2
	75th percentile	1.07	39.9	42.2	7.0	4.3
	Maximum	1.12	43.1	44.0	7.0	5.4
	Standard deviation	0.43	6.3	5.1	1.2	1.8
Park (2)	Minimum	0.45	22.5	25.3	2.7	0.1
	25th percentile	0.45	23.2	26.7	3.8	0.2
	Median	0.45	23.8	28.1	4.9	0.4
	Mean	0.45	23.8	28.1	4.9	0.4
	75th percentile	0.45	24.5	29.5	6.0	0.6
	Maximum	0.45	25.1	30.9	7.1	0.8
	Standard deviation	0.00	1.8	3.9	3.1	0.5

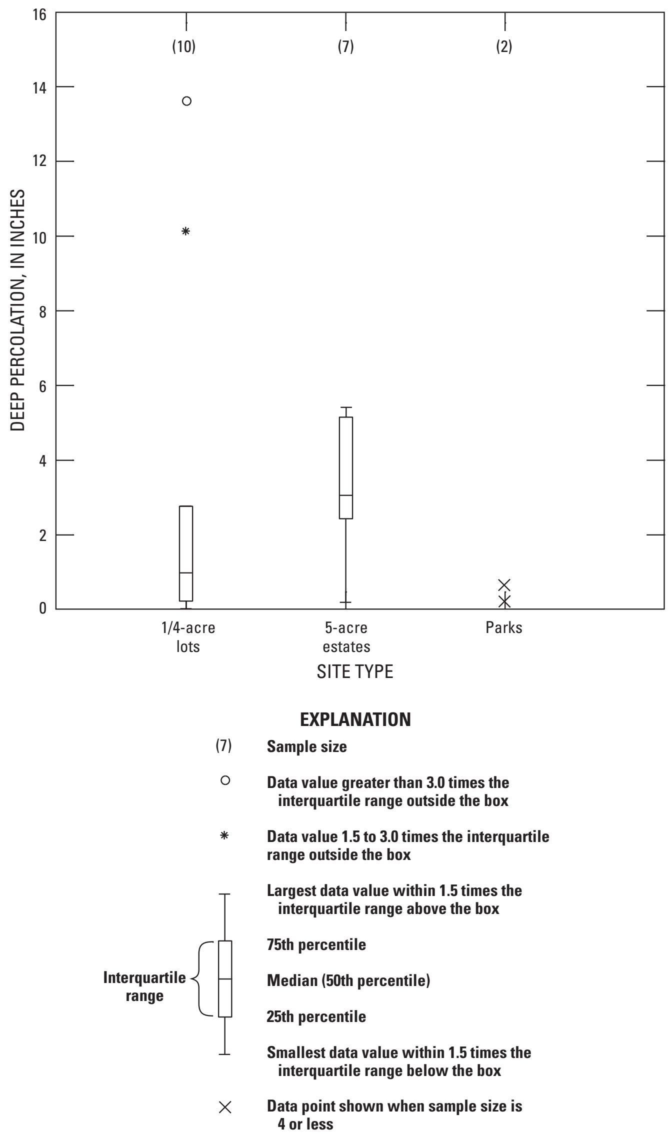


Figure 18. Deep percolation by site type for bluegrass-only vegetation sites, Grand Valley, western Colorado.

different in a statistically significant manner. Kruskal-Wallis does not indicate which group is different, only that the group medians are significantly different when the p-value is less than 0.05, indicating that the null hypothesis (each group median is identical) fails (Helsel and Hirsch, 2002).

Because the data from the study are skewed with respect to a normal distribution, the two selected statistical tests are non-parametric, meaning that they are resistant to the effect of non-normally distributed data. In both of these tests, the data are ranked from lowest to highest, and the distribution of the ranks is tested rather than the data values themselves. (Helsel and Hirsch, 2002).

For bluegrass-only sites, Kruskal-Wallis tests were performed on deep percolation results in relation to site type and study year and on effective precipitation in relation to study year. The results are listed in table 13. Data groups were considered to have different distributions (or medians) if the p-value was less than 0.05. Results indicate that deep percolation was not statistically different in each study year (p-value = 0.6797); deep percolation is not statistically different for each site type (p-value = 0.1573); and effective precipitation is statistically different in each study year (p-value = 0.0003).

Kendall's Tau correlation tests were performed on deep percolation in relation to several of the continuous variables (net irrigation applied, irrigated acres, effective precipitation, and ET) to measure the correlation between deep percolation and each variable (table 14). Additionally, ET was tested for correlation in relation to net irrigation applied. A strong correlation was considered to exist if the tau statistic was greater than 0.60. Deep percolation is strongly correlated with net irrigation applied (Tau = 0.71). Deep percolation did not strongly correlate with irrigated acres, effective precipitation, or ET. The ET correlated strongly (Tau = 0.74) with net irrigation applied.

Of interest is whether deep percolation is related causally to precipitation events, as one might suspect from the soil-moisture balance graphs that indicated deep percolation is more common during rainy periods. For some sites (for example, site 8 data for early October in figure 13), deep percolation (red columns) seem to occur simultaneously with effective precipitation events (blue columns). However, the Kendall's Tau test does not indicate a correlation, and a scatterplot of

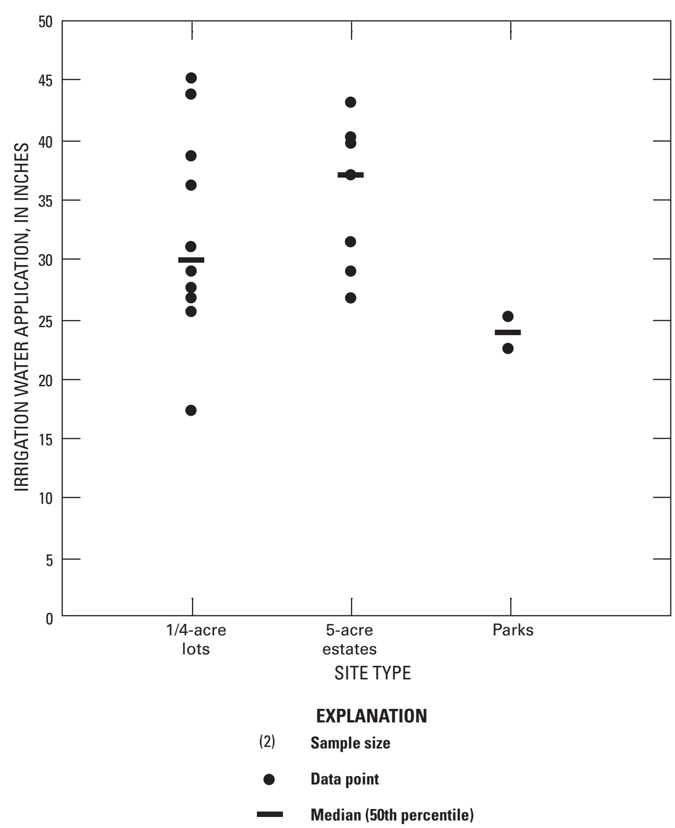


Figure 19. Irrigation-water application by site type for bluegrass-only vegetation sites, Grand Valley, western Colorado.

Table 13. Kruskal-Wallis correlation test results for bluegrass-only vegetation on residential lots, estates, and urban parks.

[Study year, 2005 or 2006; site type, residential lots, estates, and parks; effective precipitation, measured precipitation minus predicted runoff; Kruskal-Wallis statistic, test statistic for correlation; p-value, test is significant at the 95 percent level if less than (<) 0.05]

Independent variable	Dependent variable	Number of samples	Kruskal-Wallis statistic	p-value
Study year	Deep percolation	19	0.17	0.6797
Site type	Deep percolation	19	3.70	0.1573
Study year	Effective precipitation	19	13.39	0.0003

Table 14. Kendall's Tau correlation test results for bluegrass-only vegetation on residential lots, estates, and urban parks.

[Net irrigation applied, irrigation applied multiplied by irrigation efficiency; irrigated acres, acres under irrigation; effective precipitation, measured precipitation minus predicted runoff; evapotranspiration, evapotranspiration corrected for crop stress; Kendall's Tau statistic, rank correlation value; 2-tailed p-value, significant at the 95 percent level if less than (<) 0.05]

Independent variable	Dependent variable	Number of samples	Kendall's Tau statistic	2-tailed p-value
Net irrigation applied	Deep percolation	19	0.71	<0.0001
Irrigated acres	Deep percolation	19	0.27	0.1060
Effective precipitation	Deep percolation	19	0.11	0.5250
Evapotranspiration	Deep percolation	19	0.50	0.0029
Net irrigation applied	Evapotranspiration	19	0.74	<0.0001

deep percolation in relation to effective precipitation (fig. 20), shows no obvious correlation. Clearly, when the soil-moisture balance is already high due to regular irrigation, a substantial input of additional water from precipitation could put the soil-moisture balance above field capacity, resulting in deep percolation. For this data set, however, the physical mechanism of precipitation contributing to deep percolation cannot be verified statistically.

All-Vegetation Sites

Summary statistics for effective precipitation, evapotranspiration, irrigation applied, and deep percolation from 26 irrigation seasons of data for residential lots, estates, urban parks, and gated-pipe fields are provided in table 15. The mean effective precipitation was 5.7 inches, the median was 5.8 inches, and the standard deviation was 1.5 inches. The mean evapotranspiration was 30.8 inches, the median was 32.4 inches, and the standard deviation was 9.7 inches. The mean irrigation applied was 28.3 inches, while the median was 28.9 inches, with a standard deviation of 11.6. Deep percolation ranges from 0 to 20.1 inches; mean deep percolation was 3.4 inches and the median was 1.3 inches, with a standard deviation of 5.1 inches.

Summary statistics are tabulated by site type in table 16. Figure 21 shows a dot chart of deep percolation grouped by site type. Figure 22 shows a dot chart of irrigation-water application plotted by site type.

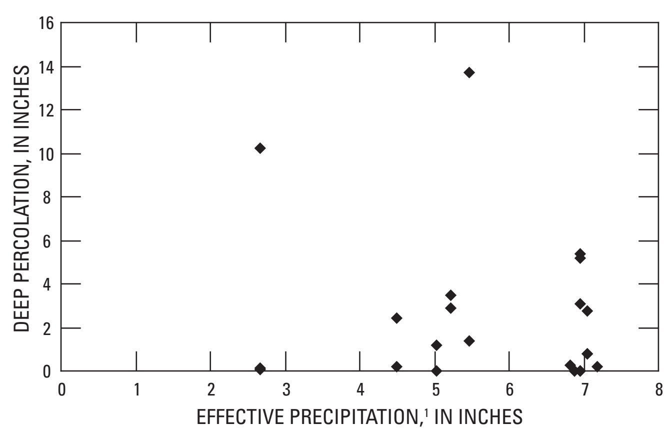
Statistical Tests for All-Vegetation Sites

Kruskal-Wallis tests were performed on deep percolation in relation to several categorical variables (study year, vegetation type, and site type). A Kruskal-Wallis test also was performed for effective precipitation in relation to study year (table 17). Results indicate effective precipitation is different each year with a high statistical significance (p-value < 0.0001). Otherwise, deep percolation is not statistically different related to study year, vegetation type, or site type.

Kendall's Tau correlation tests were performed for deep percolation in relation to several of the continuous variables (net irrigation applied, irrigated acres, effective precipitation, and ET). In addition, ET was tested for correlation with net irrigation applied (table 18). As would be expected, deep percolation correlated with net irrigation applied ($p < 0.0001$). In addition, ET correlated with net irrigation applied ($p < 0.0001$). Deep percolation correlates with ET ($p = 0.0011$) but does not correlate with irrigated acres or effective precipitation.

Whole Subdivision Deep Percolation and Irrigation-Water Application

To better understand the effects of agricultural land conversion to urban land on deep percolation in the Grand Valley, deep percolation and irrigation water applied were estimated (using aerial photographs) for all of the irrigated turf acres within the three subdivisions based on the bluegrass-site results and based on the all-vegetation type site (bluegrass, orchard grass, and native plant) results. Two of the subdivisions consisted of 1/4-acre residential lots, and the third subdivision consisted of



[1]Effective precipitation is measured precipitation minus predicted runoff

Figure 20. Deep percolation relative to effective precipitation for bluegrass-only vegetation sites, Grand Valley, western Colorado.

Table 15. Summary statistics for all-vegetation types on residential lots, estates, urban parks, and gated-pipe sites.

[Effective precipitation, measured precipitation minus predicted runoff; evapotranspiration, evapotranspiration corrected for crop stress; irrigation applied, irrigation applied multiplied by irrigation efficiency]

Statistic	Effective precipitation (inches)	Evapotranspiration (inches)	Irrigation applied (inches)	Deep percolation (inches)
Minimum	2.7	12.1	4.2	0.0
25th percentile	5.0	23.5	25.2	0.1
Median	5.8	32.4	28.9	1.3
Mean	5.7	30.8	28.3	3.4
75th percentile	7.0	38.0	36.8	3.4
Maximum	7.2	44.0	45.1	20.1
Standard deviation	1.5	9.7	11.6	5.1

Table 16. Summary statistics by site type for all-vegetation types on residential lots, estates, urban parks, and gated-pipe fields.

[Total irrigation seasons, sum of all irrigation seasons for all sites studied; net irrigation applied, irrigation applied multiplied by irrigation efficiency; stress corrected ET, evapotranspiration corrected for crop stress; effective precipitation, measured precipitation minus predicted runoff]

Site type/ (total irrigation seasons)	Statistic	Irrigated area (acres)	Net irrigation applied (inches)	Stress corrected ET (inches)	Effective precipitation (inches)	Deep percolation (inches)
1/4-acre residential lot (10)	Minimum	0.05	17.2	21.4	2.7	0.0
	25th percentile	0.05	26.9	31.3	5.0	0.2
	Median	0.08	29.9	35.5	5.5	1.0
	Mean	0.09	32.0	34.6	5.4	3.1
	75th percentile	0.12	37.9	38.0	7.0	2.4
	Maximum	0.14	45.1	42.6	7.2	13.7
	Standard deviation	0.04	8.8	6.1	1.7	4.8
5-acre estate (10)	Minimum	0.14	4.2	12.1	4.5	0.0
	25th percentile	0.56	27.3	32.2	4.7	0.5
	Median	0.82	30.6	34.0	6.1	2.6
	Mean	0.80	28.6	32.5	5.9	2.4
	75th percentile	1.10	39.0	40.5	7.0	3.4
	Maximum	1.70	43.1	44.0	7.0	5.4
	Standard deviation	0.48	13.7	11.4	1.2	2.0
Park (2)	Minimum	0.45	22.5	25.3	2.7	0.1
	25th percentile	0.45	23.2	26.7	3.8	0.2
	Median	0.45	23.8	28.1	4.9	0.4
	Mean	0.45	23.8	28.1	4.9	0.4
	75th percentile	0.45	24.5	29.5	6.0	0.6
	Maximum	0.45	25.1	30.9	7.1	0.8
	Standard deviation	0.00	1.8	3.9	3.1	0.5
Gated-pipe field (4)	Minimum	0.95	8.8	14.6	5.8	0.0
	25th percentile	0.98	9.6	15.4	5.8	0.0
	Median	0.99	18.2	18.6	6.4	6.0
	Mean	1.27	20.2	18.7	6.4	8.0
	75th percentile	1.28	28.8	21.8	7.0	14.0
	Maximum	2.13	35.8	22.9	7.0	20.1
	Standard deviation	0.58	13.1	4.1	0.7	9.8

5-acre estates. All five sites in the two 1/4-acre lot subdivisions had bluegrass. Four of the six sites in the 5-acre estate subdivision had bluegrass, one site had orchard grass, and one site had native plants. Gated-pipe sites were not included in the whole subdivision analysis. A summary of deep percolation estimates for bluegrass-only and all-vegetation type sites is provided in table 19.

To compare results for deep percolation, irrigation-water application, and salt loading between agricultural and urban sites, irrigated land areas must be equivalent. This requires taking into account the percentage of a total subdivision development that is irrigated land. The column "Total Developed Acreage of Subdivision" in table 19 is the gross land area of the subdivision, including impervious and other

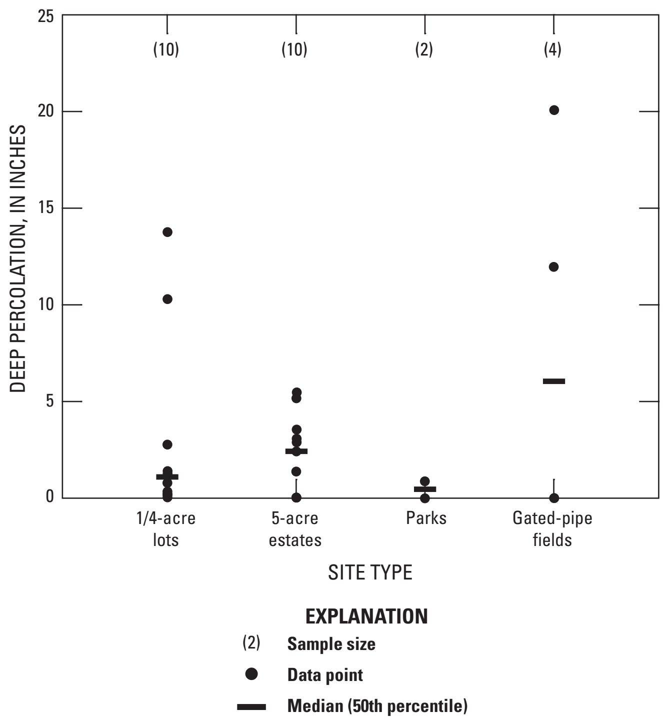


Figure 21. Deep percolation by site type for all-vegetation type sites, Grand Valley, western Colorado.

nonirrigated surfaces. It was estimated that for the three subdivisions, 37 percent (mean) of the developed acreage was irrigated (table 19). The remaining acreage was covered with nonirrigated or impermeable surfaces such as streets, houses, alleys, and sidewalks. The percentage of irrigated acreage ranged from 29 to 51 percent by subdivision. The measured results for urban study subdivisions are referred to as the values for "irrigated acreage," while the calculated values that have been reduced to reflect the percent irrigated area are referred to as the values for "developed acreage." For a subdivision, the "developed acreage" values for deep percolation, irrigation-water application, and salt loading are calculated by multiplying the "irrigated acreage" values by the percentage of irrigated area in that particular subdivision. It was assumed in this report that the NRCS M&E alfalfa-crop site acreages were 100 percent irrigated.

The mean deep percolation for study sites in the three subdivisions ranged from 2.46 to 5.12 inches, with an overall mean of 3.60 inches for bluegrass and 3.25 inches for all-vegetation type sites for the irrigation season. A mean season-total estimated deep percolation of 0.30 acre-foot per irrigated acre and 0.12 acre-foot per acre of developed area (including impervious surfaces) was calculated for bluegrass-only sites, and a mean season-total estimated deep percolation of 0.27 acre-foot per irrigated acre and 0.11 acre-foot per developed acre was calculated for all-vegetation type sites in the subdivisions. Essentially, inclusion of about 1 acre of the non-bluegrass irrigated area of Quail Run subdivision accounts for the slight difference between bluegrass-only and all-vegetation results.

A summary of estimated irrigation water applied is provided in table 20 for bluegrass-only and all-vegetation type subdivision data. The mean irrigation water applied for the bluegrass-only sites was 33.55 inches during the irrigation season, and the mean irrigation water applied for the all-vegetation type sites was 30.96 inches. A mean season-total estimated rate of 2.80 acre-feet per irrigated acre and 1.05 acre-feet per developed acre (including impervious areas) of irrigation water applied was calculated for bluegrass-only sites, and a mean estimated rate of 2.56 acre-feet per irrigated acre and 0.98 acre-foot per developed acre of irrigation water applied was calculated for all-vegetation type sites in the subdivisions.

Irrigation-Water Holding-Pond Seepage Results

Seepage results for the four irrigation seasons of irrigation-water holding-pond data are provided in table 21. The mean seepage for the four ponds during the observation period was 16.29 inches, after adjusted pan evaporation and effective precipitation were accounted for. This equated to a mean seepage of water from the four irrigation seasons of 0.83 acre-foot during the 22- to 25-day period of observation.

Projected over an entire 214-day irrigation season, a mean seepage of 143.30 inches, or a rate of 11.94 acre-feet per acre of pond surface area, would be anticipated from these ponds. This is a small sample size with data collected over a short time period; therefore, the results are not conclusive. However, the amount of seepage from the 1.086-acre

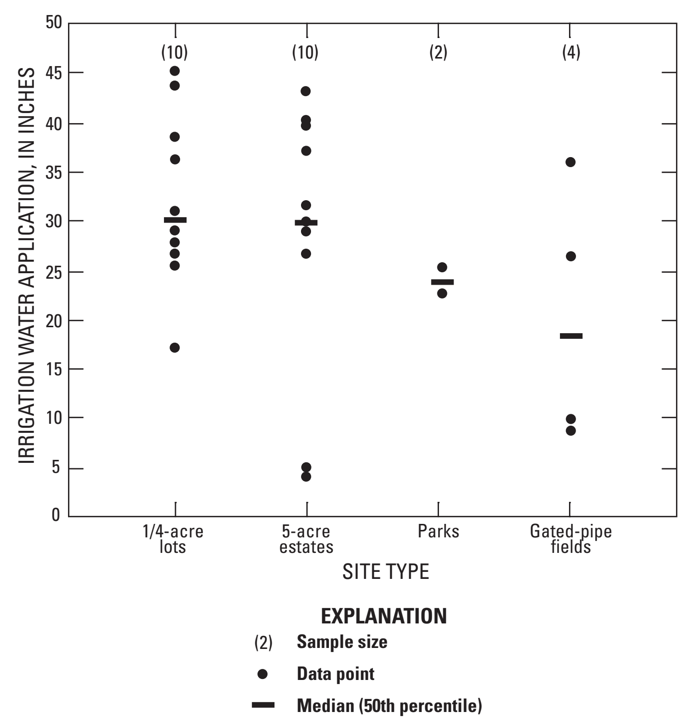


Figure 22. Irrigation-water application by site type for all-vegetation type sites, Grand Valley, western Colorado.

Table 17. Kruskal-Wallis test results for all-vegetation types on residential lots, estates, urban parks, and gated-pipe fields.

[Study year, 2005 or 2006; site type, residential lots, estates, parks, and gated-pipe fields; effective precipitation, measured precipitation minus predicted runoff; Kruskal-Wallis statistic, test statistic for correlation; p-value, test is significant at the 95 percent level if less than (<) 0.05]

Independent variable	Dependent variable	Number of samples	Kruskal-Wallis statistic	p-value
Study year	Deep percolation	26	0.07	0.7964
Vegetation type	Deep percolation	26	4.13	0.1270
Site type	Deep percolation	26	0.86	0.8349
Study year	Effective precipitation	26	19.14	<0.0001

Table 18. Kendall's Tau correlation test results for all-vegetation types on residential lots, estates, urban parks, and gated-pipe fields.

[Net irrigation applied, irrigation applied multiplied by irrigation efficiency; irrigated acres, acres under irrigation; effective precipitation, measured precipitation minus predicted runoff; evapotranspiration, evapotranspiration corrected for crop stress; Kendall's Tau statistic, rank correlation value; 2-tailed p-value, significant at the 95 percent level if less than (<) 0.05]

Independent variable	Dependent variable	Number of samples	Kendall's Tau statistic	2-tailed p-value
Net irrigation applied	Deep percolation	26	0.67	<0.0001
Irrigated acres	Deep percolation	26	0.14	0.3291
Effective precipitation	Deep percolation	26	0.13	0.3935
Evapotranspiration	Deep percolation	26	0.46	0.0011
Net irrigation applied	Evapotranspiration	26	0.77	<0.0001

Paradise Hills pond is estimated to be 11.70 (10.77 × 1.086) and 9.99 acre-feet per season (9.20 × 1.086) in 2005 and 2006, respectively. By comparison, irrigation practices for the entire 34.91 acres of irrigated bluegrass in the subdivision were estimated to generate about 15.1 acre-feet of deep percolation per season (table 19, 0.22 acre-foot per acre × 68.7 acres total developed area). A more rigorous approach to quantify seepage from perched ponds would be to measure continuously the inflow (from canal) and outflow (pumping) from the ponds over the irrigation season and correct for daily pan evaporation and precipitation. From this limited data set, it appears unlined ponds contribute far greater seasonal seepage, or deep percolation per unit area (mean 143.30 inches, table 21) than do the bluegrass urban sites (mean 2.8 inches, table 11) and gated-pipe fields (mean 8.0 inches, table 16) in the study. From these data, it seems that preventing seepage or deep percolation from ponds (by lining, for example) could yield large reductions in overall seepage and associated salt loading as land converts to residential uses from other uses such as agriculture.

Natural Resources Conservation Service Monitoring and Evaluation Deep Percolation and Irrigation-Water Application

The NRCS M&E alfalfa-crop data set contains 67 irrigation seasons of data. Figure 23 shows the frequency distribution of sites grouped by field-size category. Most sites were 40 acres or less in size.

Thirteen irrigation methods were represented in the NRCS M&E dataset, although only eight are represented among the alfalfa-crop sites used for comparison in this study (fig. 24). For alfalfa-crop sites, the predominant irrigation methods were concrete ditch to siphon tubes (n = 27 irrigation seasons of data), pipeline to gated-pipe (n = 8 irrigation seasons of data), pipeline to gated surge (n = 11 irrigation seasons of data), and side roll sprinkler (n = 13 irrigation seasons of data).

The frequency distribution of irrigation-water application for alfalfa-crop sites is shown in figure 25. Every site applied between 11 and 70 inches per irrigation season, except 1 site that applied 160 inches (not shown in figure 25 and not included for data analysis).

The frequency distribution of annual deep percolation for alfalfa-crop sites is shown in figure 26. Most sites had 29 inches or less of deep percolation per irrigation season.

Summary statistics for the alfalfa-crop sites are shown in table 22. Mean irrigation water applied was 45.4 inches and ranged from 18.9 to 69.6 inches, which generated a mean seasonal deep percolation of 15.2 inches. Summary values for acre-feet per acre also are shown in table 22.

A boxplot of NRCS M&E alfalfa-crop irrigation season-total net (total inflow minus total outflow) irrigation-water application by irrigation method is shown in figure 27. The median quantity of water applied for the three most common irrigation methods was 49.2 inches for concrete ditch siphon tubes, 43.6 inches for pipeline to gated surge, and 37.1 inches for side roll sprinkler. A Kruskal-Wallis test of irrigation-water application in relation to irrigation method showed that irrigation-water application is statistically different for each type of irrigation method (p = 0.0161).

Boxplots of NRCS M&E alfalfa-crop irrigation season-total deep percolation by irrigation method is presented in figure 28. A Kruskal-Wallis test of deep percolation compared to irrigation method showed that deep percolation is statistically different for each type of irrigation method (p = 0.0083). Median deep percolation spanned a wide range from less than 5 inches for the side roll sprinkler irrigation method to about 22 inches for pipeline to gated-pipe irrigation method.

Boxplots of NRCS M&E alfalfa-crop irrigation season-total net (total inflow less total outflow) irrigation-water application rate by site acreage is shown in figure 29. A Kendall's Tau correlation test of net irrigation-water application in relation to field size showed no strong correlation (tau = –0.07). Water application was fairly consistent among field-size categories with median values ranging from about 45 inches to just over 50 inches.

Table 19. Whole subdivision estimates of mean deep percolation for bluegrass-only sites and all-vegetation type sites.

[Total developed acreage of subdivision, total acreage of subdivision including irrigated and nonirrigated portions; all-vegetation types, includes bluegrass, orchard grass, and native plants]

Subdivision	Site type	Number of homes in subdivision	Total developed acreage of subdivision	Total irrigated acreage in subdivision	Percent irrigated area in subdivision	Bluegrass-only mean season-total deep percolation			All-vegetation types mean season-total deep percolation		
						Mean deep percolation for study sites[1] (inches)	Estimated deep percolation rate for total irrigated acreage[2] (acre-feet per acre)	Estimated deep percolation rate for total developed acreage[3] (acre-feet per acre)	Mean deep percolation for study sites[1] (inches)	Estimated deep percolation rate for total irrigated acreage[2] (acre-feet per acre)	Estimated deep percolation rate for total developed acreage[3] (acre-feet per acre)
Chipeta Pines	1/4-acre lots	63	21.14	6.03	29	2.46	0.21	0.06	[4]2.46	[4]0.20	[4]0.06
Paradise Hills	1/4-acre lots	157	68.72	34.91	51	5.12	0.43	0.22	[4]5.12	[4]0.43	[4]0.22
Quail Run	5-acre estates	33	131.72	41.62	32	3.22	0.27	0.08	2.17	0.19	0.06
Sums		**253**	**221.58**	**82.56**							
Mean		**84**	**73.86**	**27.52**	**37**	**3.60**	**0.30**	**0.12**	**3.25**	**0.27**	**0.11**

[1]Based on data collected at individual bluegrass-only or all-vegetation sites during 2005 and 2006 for each subdivision.

[2]Estimated deep percolation rate for total irrigated acreage = mean deep percolation for subdivision study sites divided by 12 inches per foot.

[3]Estimated deep percolation rate for total developed acreage = estimated deep percolation rate for total irrigated acreage multiplied by percent irrigated acreage in subdivision.

[4]All-vegetation values are the same as bluegrass-only because bluegrass was the only irrigated vegetation type included in the study for this subdivision.

Table 20. Whole subdivision estimates of mean irrigation water applied for bluegrass-only sites and all-vegetation type sites.

[Total developed acreage of subdivision, total acreage of subdivision including irrigated and nonirrigated portions; all-vegetation types, includes bluegrass, orchard grass, and native plants]

Subdivision	Site type	Number of homes in subdivision	Total developed acreage in subdivision	Total irrigated acreage for subdivision	Percent irrigated acreage in subdivision	Bluegrass-only vegetation season-total irrigation-water application			All-vegetation types mean season-total irrigation-water application		
						Mean irrigation-water application for study sites[1] (inches)	Estimated irrigation-water application rate for total irrigated acreage[2] (acre-feet per acre)	Estimated irrigation-water application rate for total developed acreage[3] (acre-feet per acre)	Mean irrigation-water application for study sites[1] (inches)	Estimated irrigation-water application rate for total irrigated acreage[2] (acre-feet per acre)	Estimated irrigation-water application rate for total developed acreage[3] (acre-feet per acre)
Chipeta Pines	1/4-acre lots	63	21.14	6.03	29	29.18	2.43	0.69	[4]29.18	[4]2.43	[4]0.69
Paradise Hills	1/4-acre lots	157	68.72	34.91	51	36.23	3.02	1.53	[4]36.23	[4]3.02	[4]1.53
Quail Run	5-acre estates	33	131.72	41.62	32	35.26	2.94	0.93	26.83	2.24	0.71
Sums		**253**	**221.58**	**82.56**							
Mean		**84**	**73.86**	**27.52**	**37**	**33.55**	**2.80**	**1.05**	**30.96**	**2.56**	**0.98**

[1]Based on data collected at individual bluegrass-only or all-vegetation sites during 2005 and 2006 for each subdivision.

[2]Estimated irrigation-water application rate for irrigated acreage = mean irrigation-water application for study sites divided by 12 inches per foot.

[3]Estimated irrigation-water application rate for total developed acreage = estimated irrigation-water application rate for total irrigated acreage multiplied by percent irrigated acreage in subdivision.

[4]All-vegetation values are the same as bluegrass-only, because bluegrass was the only irrigated vegetation type included in the study for this subdivision.

Table 21. Seepage results for irrigation-water holding ponds, 2005–2006.

[Surface area of pond, water surface area at beginning of observations; adjusted pan evaporation, measured pan evaporation multiplied by mean annual pan coefficient of 0.70 for western Colorado to obtain lake evaporation; seepage during test period, observed stage change minus total pan evaporation plus total daily precipitation; estimated deep percolation per season, seepage during test period divided by number of days observed multiplied by number of days per irrigation season]

Year	Pond (site number)	Surface area of pond (acres)	Number of days observed	Observed stage change (inches)	Adjusted pan evaporation (inches)	Total daily precipitation (inches)	Seepage during test period (inches)	Seepage during test period (acre-feet)	Estimated deep percolation[1] per season[2] (inches)	Estimated deep percolation[1] per season[2] (acre-feet per surface acre)
2005	Paradise Hills (26)	1.086	22	14.64	1.47	0.12	13.29	1.20	129.29	10.77
2006	Paradise Hills (26)	1.086	25	14.40	1.70	0.19	12.89	1.17	110.36	9.20
2006	Quail Run (27)	0.318	25	24.12	1.70	0.19	22.61	0.60	193.57	16.13
2006	Chipeta Pines (28)	0.157	25	17.88	1.70	0.17	16.35	0.35	139.98	11.67
Mean		**0.662**		**17.76**	**1.64**	**0.17**	**16.29**	**0.83**	**143.30**	**11.94**

[1]Pond seepage is assumed to be equivalent to deep percolation for this analysis.

[2]An irrigation season is approximately 214 days.

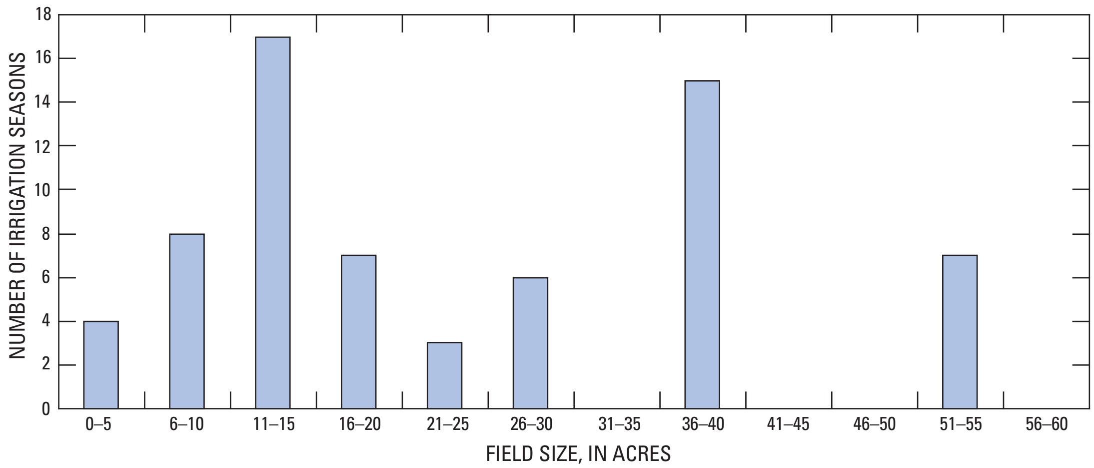


Figure 23. Frequency distribution of field sizes included in Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

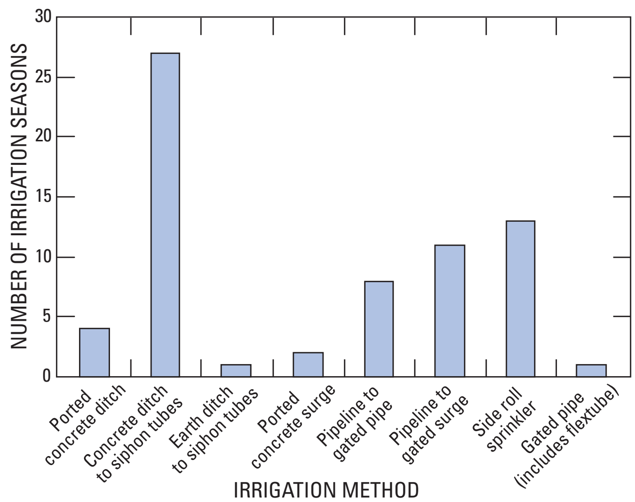


Figure 24. Frequency distribution of irrigation methods for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

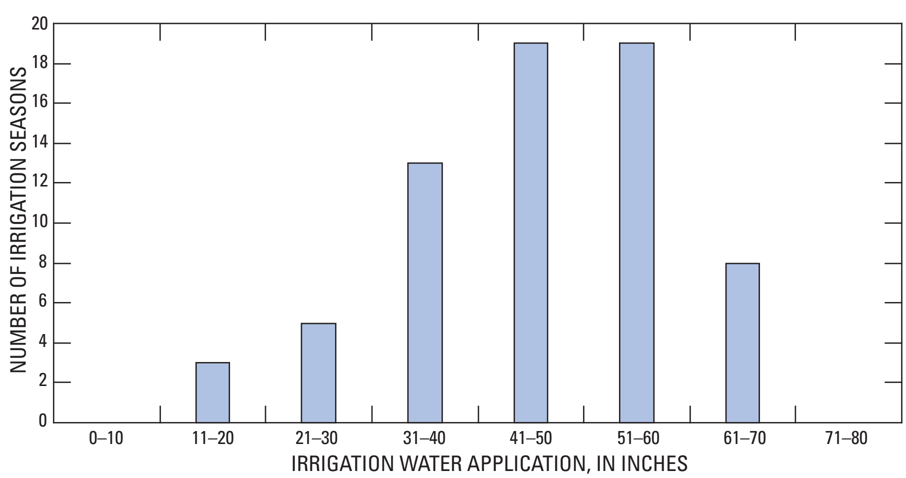


Figure 25. Frequency distribution of irrigation-water application for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

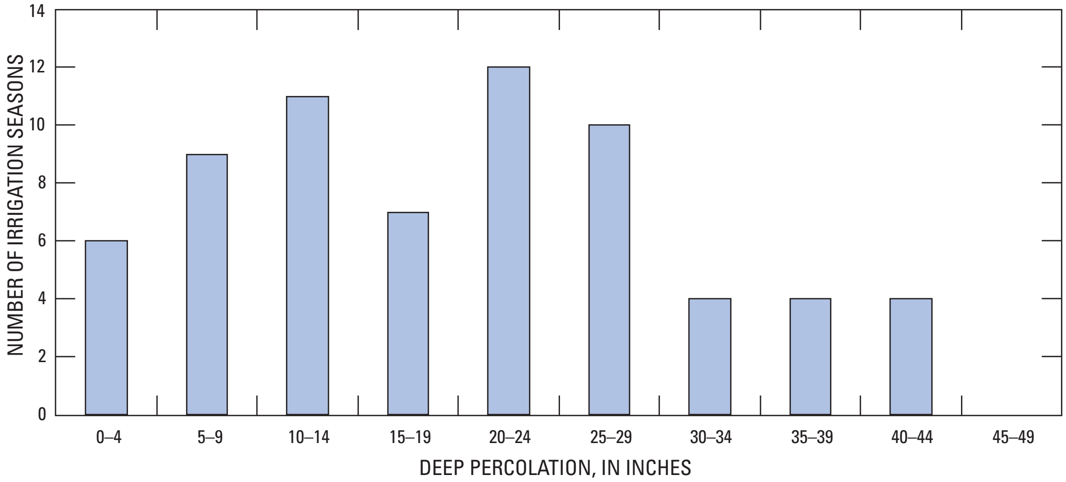


Figure 26. Frequency distribution of deep percolation for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

Table 22. Summary statistics for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

[Total irrigation seasons, sum of all irrigation seasons for all sites studied]

Total irrigation seasons	Statistic	Irrigation water applied (inches)	Irrigation water applied (acre-feet per irrigated acre)	Deep percolation (inches)	Deep percolation (acre-feet per irrigated acre)
67	Minimum	18.9	1.58	0.0	0.00
67	25th percentile	36.6	3.05	6.1	0.50
67	Median	46.8	3.79	15.2	1.30
67	Mean	45.4	3.79	15.2	1.27
67	75th percentile	54.9	4.57	23.0	1.92
67	Maximum	69.6	5.80	39.2	3.27
67	Standard deviation	1.4	1.02	10.4	0.92

Boxplots of NRCS M&E alfalfa-crop site annual deep percolation by site acreage is shown in figure 30. A Kendall's Tau correlation of deep percolation by site acreage showed no strong correlation (tau = –0.10). Deep percolation was somewhat more variable than water application by field-size category with medians ranging from less than 5 inches to greater than 20 inches.

Comparison of Results Between this Study and the Natural Resources Conservation Service Monitoring and Evaluation

There are two questions of interest for understanding the effect on salt loading from the conversion of agricultural land to urban land: (1) what quantity of irrigation water is applied to crops and turf grass, respectively, and (2) how much deep percolation is generated for a given acre of agricultural land compared to an acre of urban land in the Grand Valley?

A related question is whether bluegrass, which is the predominant type of irrigated vegetation in the subdivisions in the Grand Valley, has a different pattern of irrigation-water application and deep percolation than does the mix of vegetation types found in the 5-acre estates.

Deep Percolation and Irrigation-Water Application Rates

Results from this study indicated that 37 percent (mean) of the developed subdivision acreage was irrigated (table 19). The remainder either was covered with streets, houses, and sidewalks or was not intensively irrigated. By comparison, an estimated 2 to 3 percent of agricultural land is nonirrigated, although the NRCS M&E only included irrigated acreage in its monitoring (Frank Riggle, written commun., 2007). For this reason, in the current analysis the agricultural alfalfa-crop fields in the NRCS M&E were assumed to be 100 percent irrigated. Because this urban study measured water application and deep percolation on vegetated surfaces only and these are on average only 37 percent of a subdivision's total developed area, a direct comparison between an acre of subdivision land and an acre of agricultural land requires application of a 37-percent correction factor for water application and deep percolation results for the residential subdivision sites.

Table 23 lists summary statistics for comparison of deep percolation between agricultural alfalfa-crop and urban bluegrass-only and all-vegetation type sites in subdivisions. The estimated mean deep percolation for the urban study bluegrass-only sites

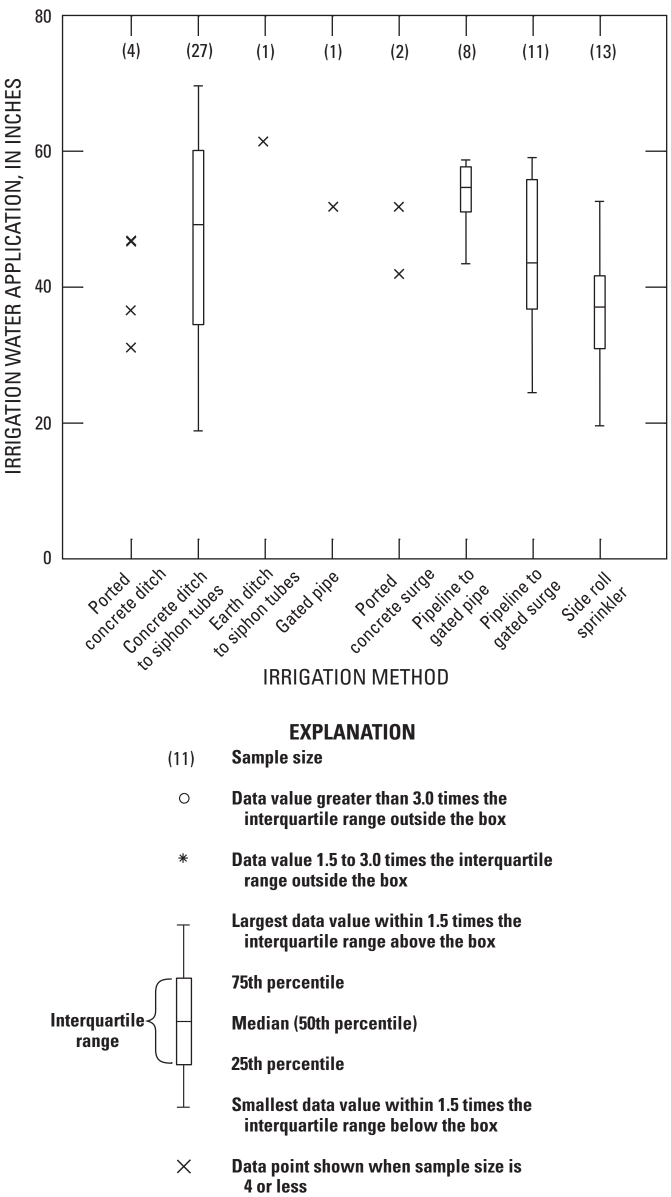


Figure 27. Season-total irrigation-water application by irrigation method for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa sites (1985–2002).

is 0.12 acre-foot per developed acre, while the estimated mean deep percolation for all-vegetation type sites in subdivisions is slightly lower at 0.11 acre-foot per developed acre. The mean deep percolation for alfalfa-crop sites in the NRCS M&E is 1.27 acre-feet per irrigated acre, which is 10.6 times greater than the mean deep percolation for bluegrass-only sites and 11.5 times greater than for all-vegetation types in the three subdivisions. For equivalent land areas, as land is converted from agricultural to urban residential uses, this represents a potential deep percolation reduction of 91 percent for all-vegetation type sites and a potential reduction of 91 percent for bluegrass-only sites. Worth noting, the NRCS M&E data represent 11 irrigation seasons of weather conditions, while the current study included only 2 years of irrigation seasons.

Table 24 shows summary statistics for comparison of irrigation-water application between agricultural alfalfa-crop and urban bluegrass and all-vegetation types. Again, the raw urban study irrigation-water application values are multiplied by 37 percent for this comparison, so the results give acre-feet per developed acre. The mean irrigation-water application rate for bluegrass-only sites is 1.05 acre-feet per developed acre, while the mean irrigation-water application rate for all-vegetation type sites in subdivisions is 0.98 acre-foot per developed acre. The mean application rate for alfalfa-crop sites is 3.79 acre-feet per acre per irrigated acre, a ratio of 3.6 times more irrigation water applied for agriculture compared to bluegrass-only sites, and a ratio of 3.9 times more irrigation water applied compared to the all-vegetation type sites in subdivisions. For equivalent land areas, compared with agricultural sites, this represents a reduction of 74 percent in irrigation-water application for all-vegetation type sites and a reduction of 72 percent for bluegrass-only sites in subdivisions.

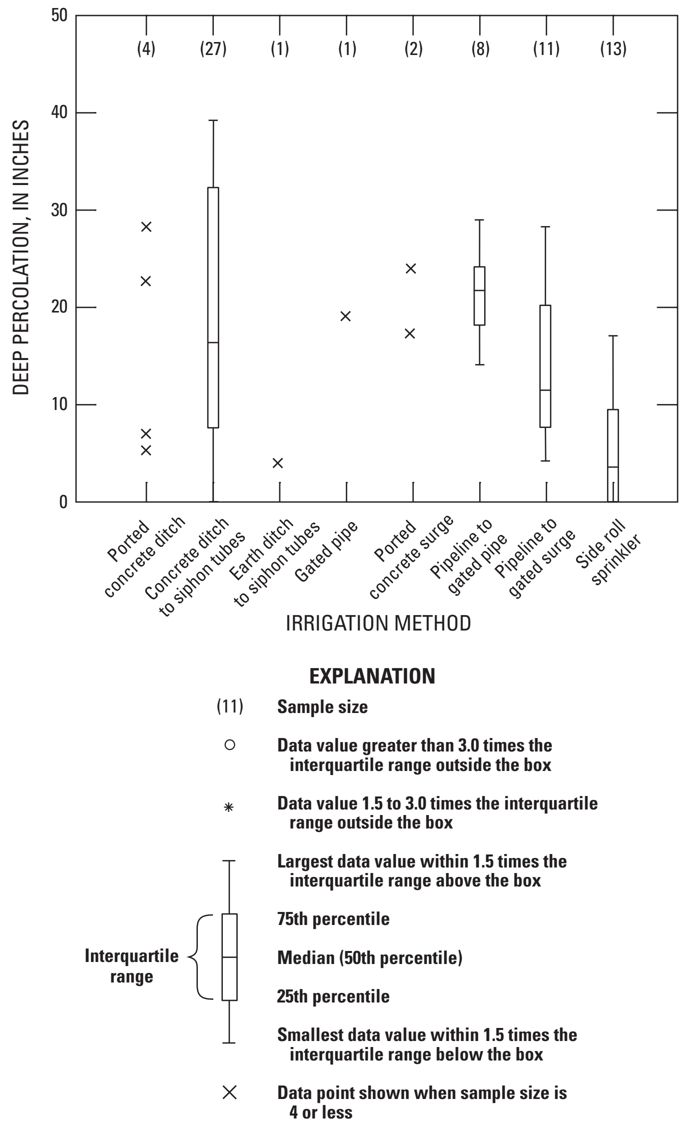


Figure 28. Distribution of season-total deep percolation by irrigation method for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

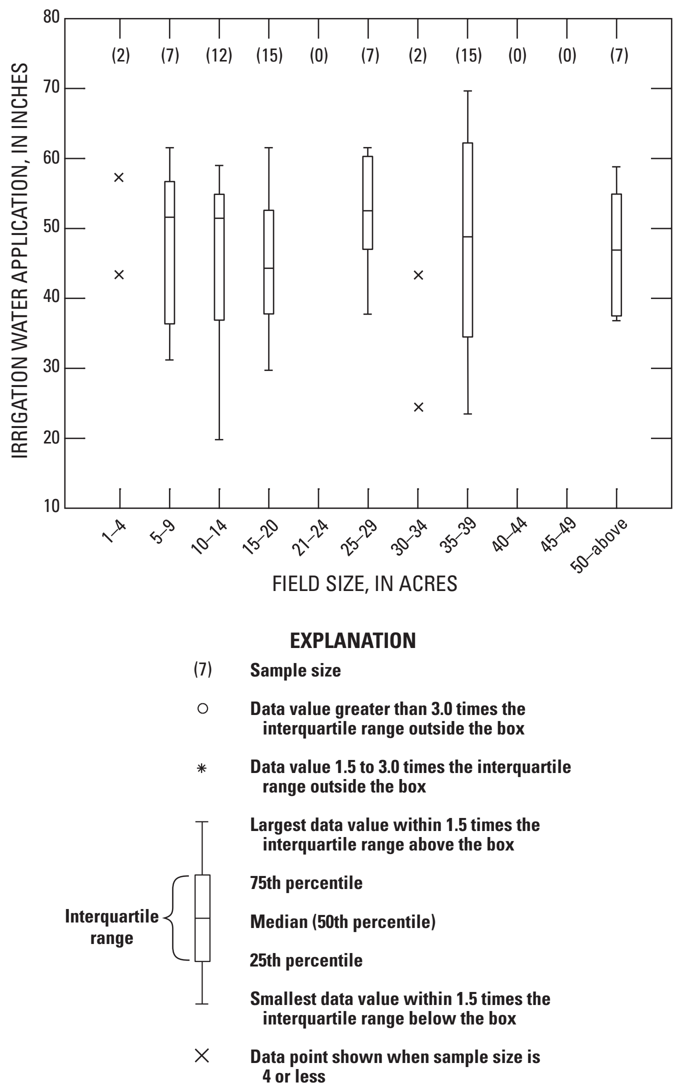


Figure 29. Season-total irrigation-water application by site acreage for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa sites (1985–2002).

It is the conclusion of this study that conversion of agricultural land to residential subdivisions in the Grand Valley of western Colorado decreases irrigation-water application and its associated deep percolation. This is true when comparing equivalent irrigated areas and even more so considering the subdivisions in this study only irrigated about 37 percent of the total land area as compared to 97–98 percent of the agricultural land (alfalfa) that is taken out of production.

Salt Loading

Relative salt loading for urban and agricultural land is listed in table 25. The mean salt loading rate to the Colorado River from bluegrass-only study sites is 0.25 ton per developed acre and 0.22 ton per developed acre for all-vegetation types, assuming that 37 percent of urban land is irrigated land. The slightly decreased mean for all-vegetation types is explained by the inclusion of native plant and orchard grass sites, which have lower deep percolation. Mean salt loading for NRCS M&E alfalfa-crop sites was 2.60 tons per acre. As a ratio, compared with alfalfa-crop sites, this represents a salt loading reduction factor of 10.4 for bluegrass-only sites and a reduction factor of 11.8 for all-vegetation type sites. Subdivision irrigation-water holding ponds were estimated to generate about 24.48 tons per surface acre of salt loading, a ratio increase over agricultural alfalfa-crop sites of 9.4.

Thus, the conversion of agricultural land to residential urban subdivisions results in substantially lower irrigation-water application, deep percolation, and salt loading per developed acre, with the exception of urban unlined ponds. Control of deep percolation from unlined ponds that are created to support residential irrigation could be an increasingly important factor to consider for minimizing irrigation-induced salt loading to the Colorado River.

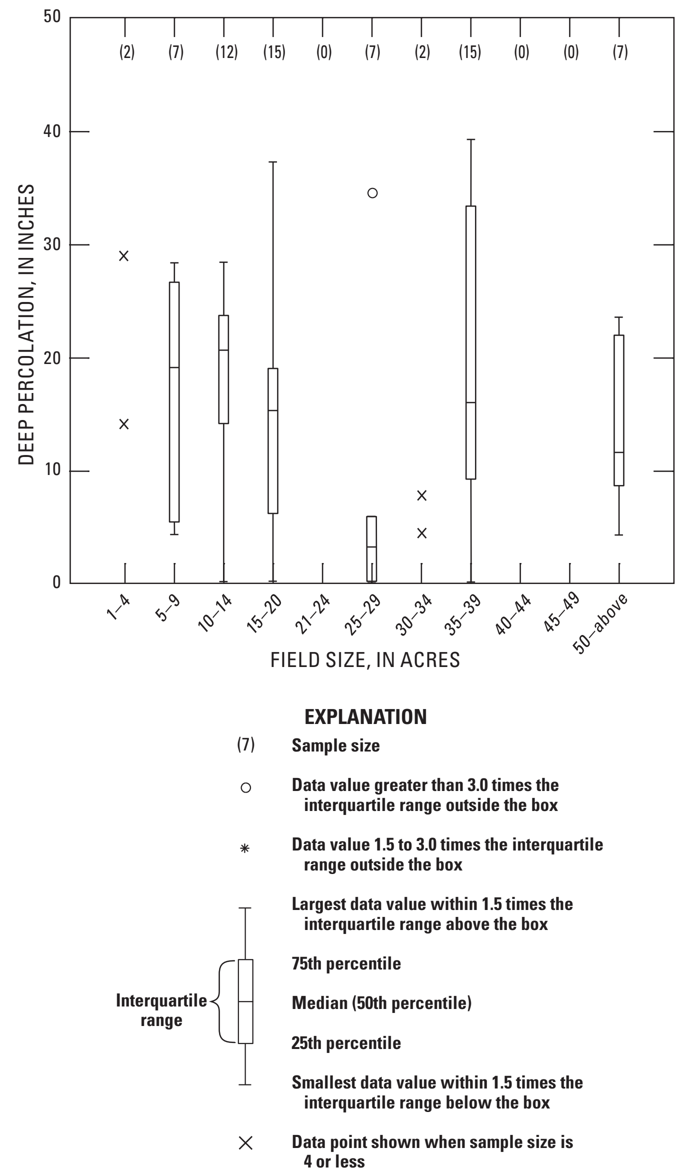


Figure 30. Distribution of season-total deep percolation by site acreage for Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites (1985–2002).

Table 23. Deep percolation comparison statistics for urban study whole subdivision bluegrass-only sites, all-vegetation type sites, and Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites.

	Urban study estimated deep percolation for total developed acreage (acre-feet per developed acre)		NRCS M&E deep percolation (acre-feet per irrigated acre)
	Bluegrass-only vegetation	All-vegetation types	Alfalfa-crop sites
Minimum	0.06	0.06	0.00
Mean	0.12	0.11	1.27
Maximum	0.22	0.22	3.27

Table 24. Irrigation-water application comparison statistics for urban study whole subdivision bluegrass-only sites, all-vegetation type sites, and Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) alfalfa-crop sites.

	Urban study estimated irrigation water application for total developed acreage (acre-feet per developed acre)		NRCS M&E irrigation-water application (acre-feet per irrigated acre)
	Bluegrass-only vegetation	All-vegetation types	Alfalfa-crop sites
Minimum	0.69	0.69	1.58
Mean	1.05	0.98	3.79
Maximum	1.53	1.53	5.80

Table 25. Salt loading comparisons for urban study whole subdivision sites and Natural Resources Conservation Service Monitoring and Evaluation (NRCS M&E) sites.

[Mean salt loading, mean deep percolation multiplied by salt loading factor multiplied by standard return factor]

Category	Mean deep percolation (acre-feet per developed acre)	Salt loading factor (tons per acre-feet)[1]	Standard return factor[2]	Mean salt loading (tons per developed acre)
Urban bluegrass-only vegetation subdivisions	0.12	4.1	0.5	0.25
Urban all-vegetation type subdivisions	0.11	4.1	0.5	0.22
Subdivision irrigation-water holding ponds	11.94	4.1	0.5	24.48
NRCS M&E alfalfa-crop sites	1.27	4.1	0.5	2.60

[1]Salt loading factor is the quantity of salt reaching the Colorado River in tons of salt per acre-foot of irrigation-induced deep percolation (Hedlund, 1994).

[2]Standard Return Factor is a correction for deep percolation and seepage that is picked up and reused by lower lying irrigation systems, intercepted by deep-rooted plants such as shrubs and trees, used by phreatophytic plants, evaporated in irrigation-induced wetlands, or used by vegetation along the irrigation drains. The value of 0.50 is a standard determined administratively by NRCS for use in Utah, Colorado, and Wyoming (Frank Riggle, Natural Resources Conservation Service, oral commun., 2007).

Summary

The conversion of agricultural land to urban residential land is associated with rapid population growth in the Grand Valley of western Colorado. Information regarding the effects of this land-use conversion on deep percolation, irrigation-water application, and associated salt loading to the Colorado River is needed to support water-resource planning and conservation efforts.

The Natural Resources Conservation Service (NRCS) assessed deep percolation and estimated salt loading derived from irrigated agricultural lands in the Grand Valley in a 1985 to 2002 monitoring and evaluation study (NRCS M&E). The U.S. Geological Survey (USGS), in cooperation with the Colorado River Salinity Control Forum and the Mesa Conservation District, quantified (the "urban study") the current (2005–2006) deep percolation and irrigation-water application characteristics of 1/4-acre residential lots and 5-acre estates, urban parks, and urban orchard grass fields in the Grand Valley and compared the results to NRCS M&E results from alfalfa-crop sites. In addition, pond seepage from three irrigation-water holding ponds was estimated. Salt loading was estimated for the urban study results and the NRCS M&E results using standard salt loading factors for the Grand Valley. A daily soil-moisture balance calculation technique was used at all urban study irrigated sites. Deep percolation was defined as any water infiltrating below the top 12 inches of soil. Deep percolation occurred when the soil-moisture balance in the first 12 inches of soil exceeded the field capacity for the soil type at each site.

Historically, agriculture in the Grand Valley has been provided with ample and inexpensive irrigation water, which is canal-delivered from the Colorado and Gunnison Rivers. Geologically, the Grand Valley is underlain by the Mancos Shale, which is a nonpoint source for salt and trace elements such as selenium. Deep percolation of irrigation waters in the Grand Valley leaches considerable salt and selenium from Mancos Shale-derived soils and Mancos Shale bedrock. Upstream from the irrigated area of the Grand Valley, selenium concentrations are generally less than 1 part per billion (ppb), while downstream from irrigated areas, selenium concentrations commonly exceed 4.6 ppb, the State of Colorado chronic standard for aquatic life.

The urban study quantified the 2005 and 2006 irrigation-water application and deep percolation characteristics at 21 urban sites, yielding 30 irrigation seasons of data. The Grand Valley urban study sites consisted of seven residential lots, six 5-acre estates, one urban park, four orchard grass fields (using gated-pipe flood irrigation), and three irrigation-water holding ponds. Twelve of the 18 residential sites had bluegrass, 5 had orchard grass, and 1 had native western Colorado plants. Results were reported separately for the bluegrass-only sites and for all-vegetation type urban study sites. Deep percolation, irrigation-water application, and salt loading also were estimated for a complete irrigation season at three of the subdivisions using mean site data from each subdivision.

Irrigated urban study sites were instrumented with digital data loggers to record the activity of sprinkler-timers, water pressure, and water-flow rate per irrigation zone. In addition, homeowners kept written logs of their irrigation activities. Precipitation was measured at each subdivision and at two Grand Valley locations and was corrected for storm runoff effects. Soil-moisture samples were collected periodically for determination of gravimetric soil-moisture content and soil bulk density. Orchard grass fields had water inflow measured with flow meters and outflow (tail-water) measured with broad-crested flumes. Irrigation-water holding ponds were equipped with USGS staff plates for water-level (stage) measurements.

Daily evapotranspiration (ET) was calculated from local climate data using the dual crop-coefficient version of the Penman-Monteith equation, as described in the Food and Agriculture Organization (FAO) irrigation and drainage paper 56. The dual crop coefficients were corrected daily for crop stress. The NRCS M&E deep percolation and ET calculation methods were examined and were determined to be comparable to the urban study calculation methods for purposes of deep percolation comparison.

A daily soil-moisture balance calculation technique was created for each irrigated urban site that included moisture inputs (precipitation and irrigation-water application) and outputs (evapotranspiration, runoff, and deep percolation). Parameters in the soil-moisture balance model accounted for irrigation water runoff and overspray, irrigation efficiency, crop height, and soil physics (soil type, field capacity, and wilting point). Gravimetric soil-moisture sample values were correlated periodically with the calculated soil-moisture balance values. Whole subdivision irrigation-water application and deep percolation were estimated using mean values for the urban study sites in each subdivision and the total irrigated acreage for each subdivision.

An area-capacity curve was created for each irrigation-water holding pond by topographic survey. The area-capacity curves allowed conversion of pond stage to volume of pond water. Deep percolation (seepage) from irrigation-water holding ponds was calculated from pond-water volume changes and local pan evaporation after the end of the irrigation season.

Salt loading in the Colorado River was calculated for the urban study sites and the NRCS M&E alfalfa-crop sites using standard loading factors and standard average return-flow reductions for the Grand Valley. NRCS M&E alfalfa-crop sites were selected for comparison with the urban study-site results because alfalfa is a widely grown crop in the Grand Valley and commonly is the agricultural crop that is grown prior to urban residential land-use conversion. Alfalfa also represents a substantial portion of the NRCS M&E data set and is one of the standard reference crops for evapotranspiration calculations.

To compare results for deep percolation, irrigation-water application, and salt loading between agricultural and urban sites, the irrigated land areas must be equivalent. This requires taking into account the percentage of a total subdivision development that is irrigated land. It was estimated, using aerial photographs of three subdivisions, that 37 percent (mean) of the developed subdivision acreage was irrigated (the balance being nonirrigated or impermeable surfaces). The percentage irrigated acreage ranged from 29 to 51 percent by subdivision. The measured results for urban study subdivisions are referred to as the values for "irrigated acreage," whereas the calculated values which have been reduced to reflect the percent irrigated area are referred to as the values for "developed acreage." For a subdivision, the "developed acreage" values for deep percolation, irrigation-water application, and salt loading are calculated by multiplying the "irrigated acreage" values by the percentage of irrigated area in that particular subdivision. For the urban study, it was assumed that the NRCS M&E alfalfa-crop site acreages were 100 percent irrigated.

The mean season-total deep percolation for bluegrass-only sites at the three residential subdivisions was 0.30 acre-foot per irrigated acre and 0.12 acre-foot per developed acre. The season-total deep percolation for all-vegetation types at the three subdivisions was 0.27 acre-foot per irrigated acre and 0.11 acre-foot per developed acre. On the basis of a limited data set, mean season-total irrigation-water holding-pond deep percolation (seepage) was estimated to be 11.94 acre-feet per surface acre.

The mean season-total irrigation-water application for bluegrass-only sites in subdivisions was 2.80 acre-feet per irrigated acre and 1.05 acre-feet per developed acre. The mean season-total irrigation-water application for all-vegetation type sites at residential subdivisions was 2.56 acre-feet per irrigated acre and 0.98 acre-foot per developed acre.

Mean season-total deep percolation for alfalfa-crop sites in the NRCS M&E was 1.27 acre-feet per acre. For equivalent land areas, the conversion of land from agricultural to urban residential uses results in a potential deep percolation reduction of 91 percent for bluegrass-only sites and a potential reduction of 91 percent for all-vegetation type sites. Mean season-total irrigation-water application for alfalfa-crop sites in the NRCS M&E was 3.79 acre-feet per developed acre. For equivalent land areas, this represents a reduction of 72 percent in irrigation-water application for bluegrass-only sites compared with agricultural sites and a reduction of 74 percent for all-vegetation type sites.

Salt loading to the Colorado River for urban bluegrass-only sites was estimated to be 0.25 ton per developed acre and for all-vegetation type sites was estimated to be 0.22 ton per developed acre. Mean salt loading for NRCS M&E alfalfa-crop sites was 2.60 tons per acre. As a ratio, compared with alfalfa-crop sites, this represents a salt-loading reduction factor of 10.4 for bluegrass-only sites, and a reduction factor of 11.8 for all-vegetation type sites. Salt loading from ponds was estimated to be 24.48 tons per surface acre, a ratio increase over agricultural alfalfa-crop sites of 9.4.

Thus, the conversion of agricultural land to residential urban subdivisions results in substantially lower irrigation-water application, lower deep percolation, and less salt loading per developed acre, with the exception of urban unlined ponds. Control of deep percolation from unlined ponds that are created to support residential irrigation could be an increasingly important factor to consider for minimizing irrigation-induced salt loading to the Colorado River.

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Appendixes

Appendix 1. Season Water Balance Charts for All Sites

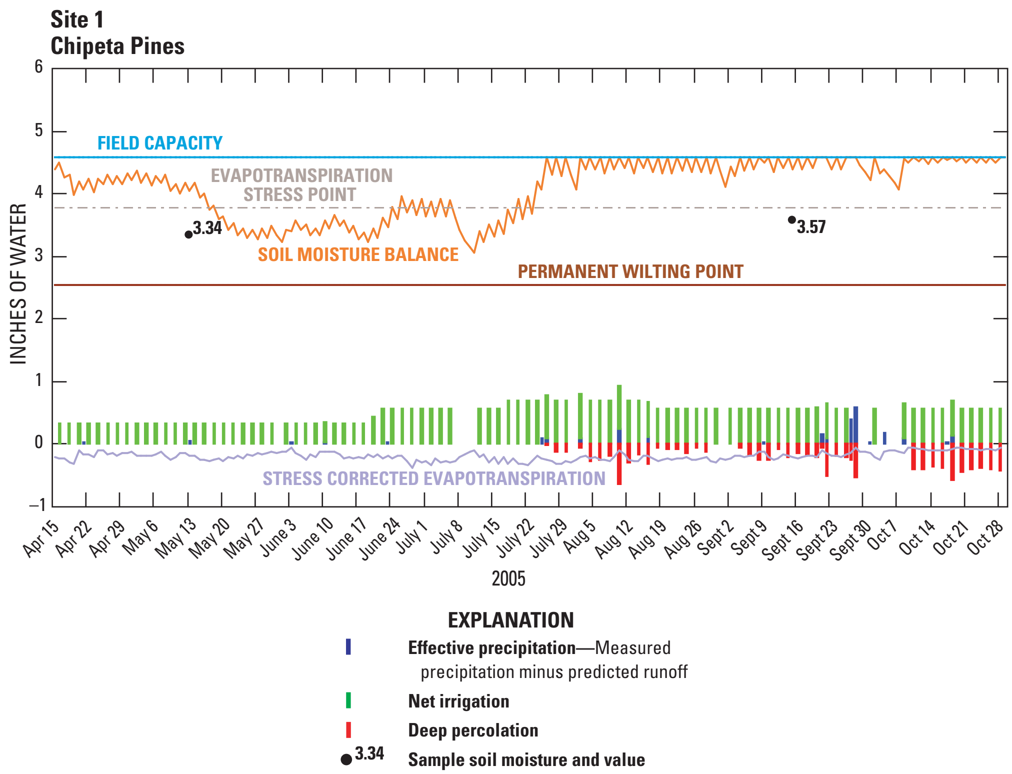


Figure A1. Soil-moisture balance for 2005 season, site 1, Grand Valley, western Colorado.

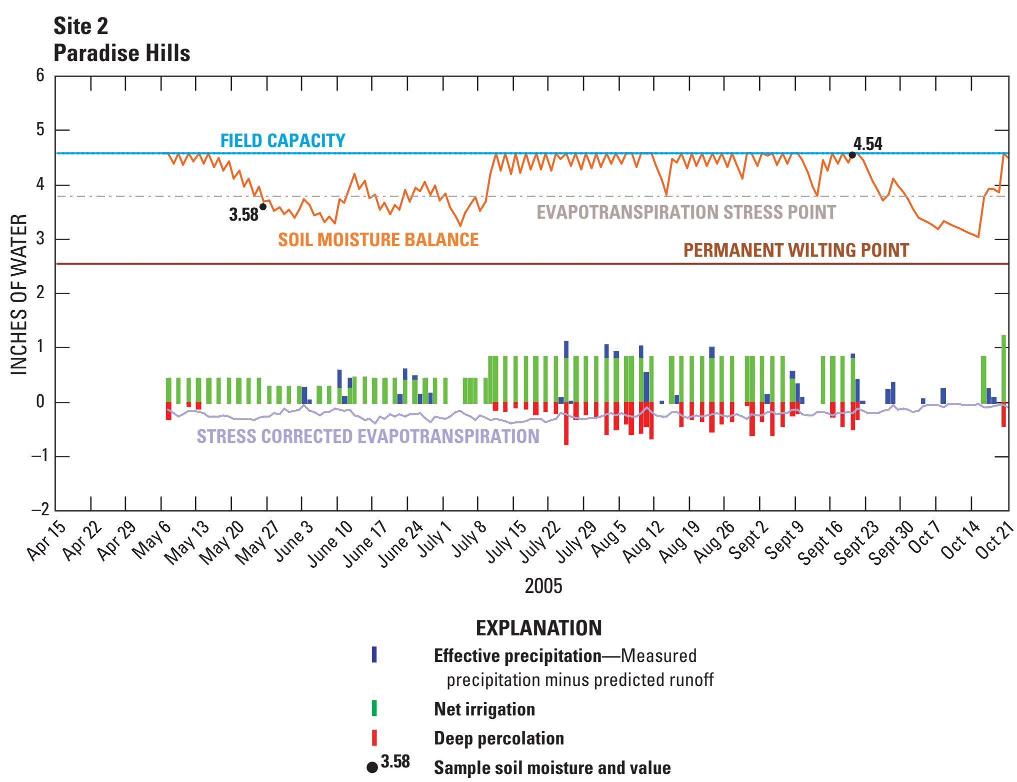
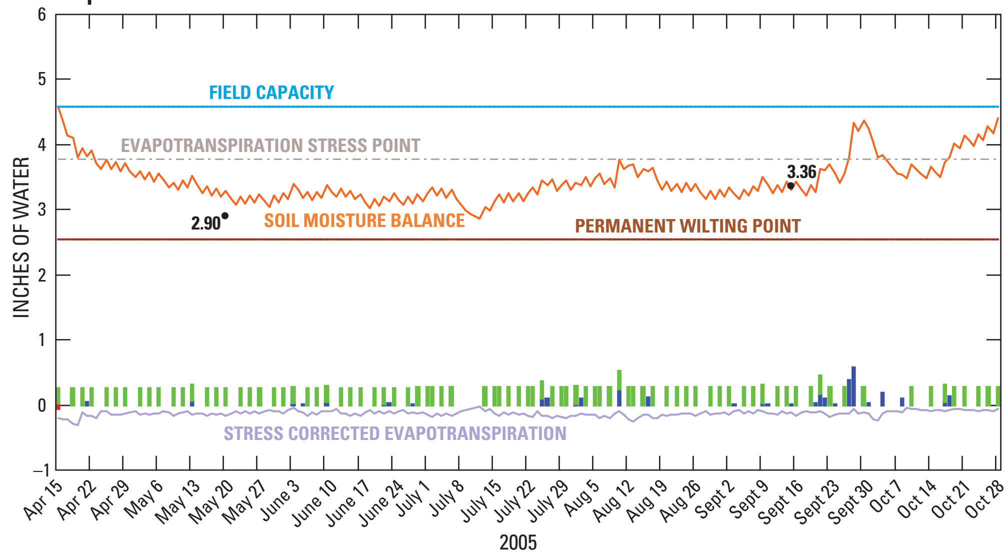


Figure A2. Soil-moisture balance for 2005 season, site 2, Grand Valley, western Colorado.

Site 6
Chipeta Pines

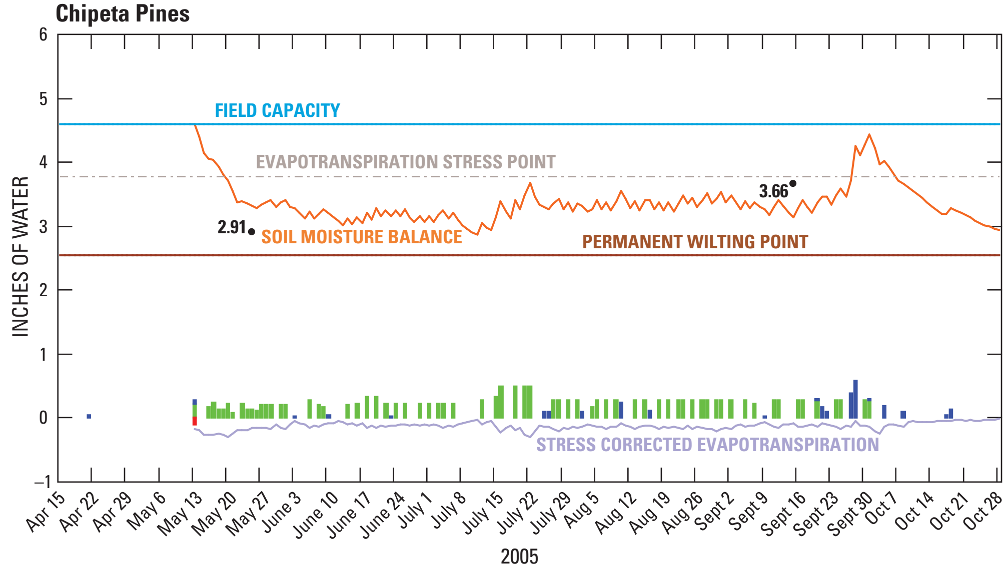


EXPLANATION

- **Effective precipitation**—Measured precipitation minus predicted runoff
- **Net irrigation**
- **Deep percolation**
- 2.90 **Sample soil moisture and value**

Figure A3. Soil-moisture balance for 2005 season, site 6, Grand Valley, western Colorado.

Site 8
Chipeta Pines



EXPLANATION

- **Effective precipitation**—Measured precipitation minus predicted runoff
- **Net irrigation**
- **Deep percolation**
- 2.91 **Sample soil moisture and value**

Figure A4. Soil-moisture balance for 2005 season, site 8, Grand Valley, western Colorado.

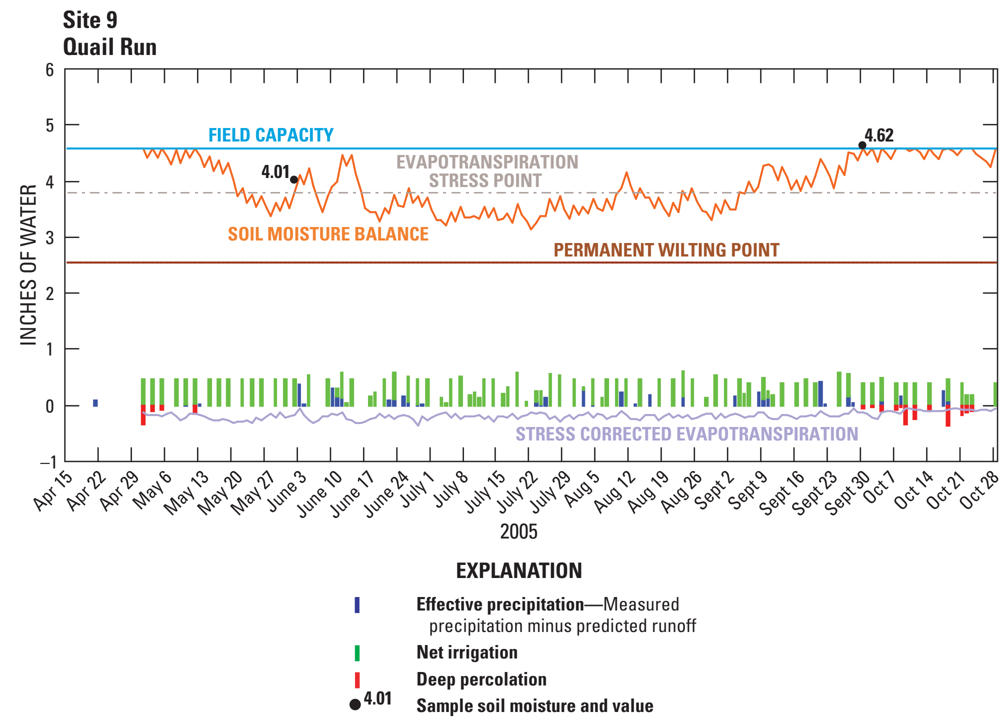


Figure A5. Soil-moisture balance for 2005 season, site 9, Grand Valley, western Colorado.

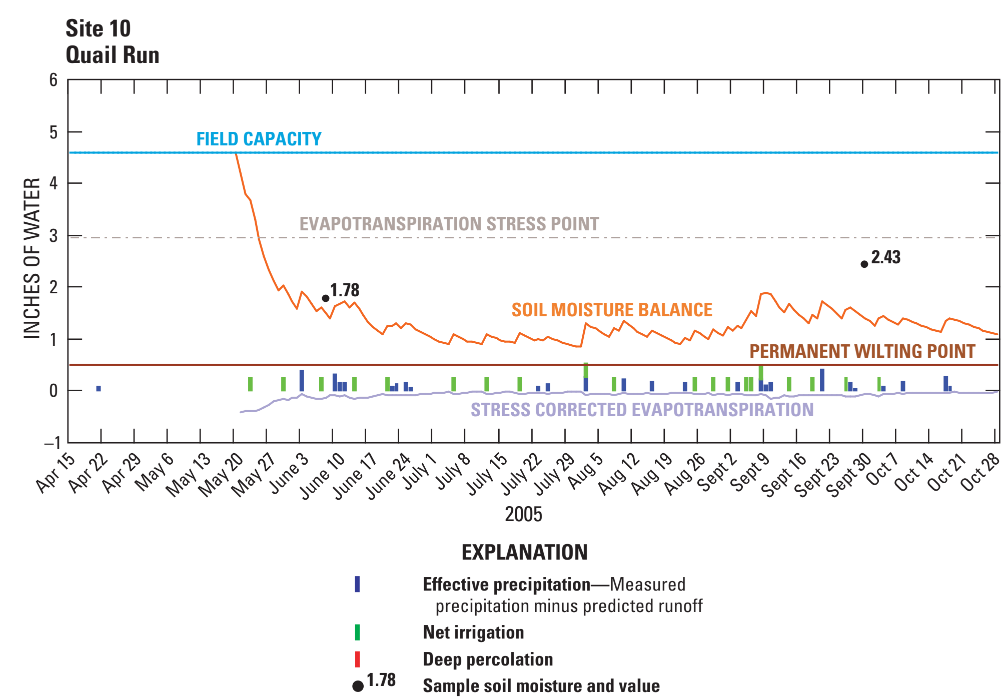


Figure A6. Soil-moisture balance for 2005 season, site 10, Grand Valley, western Colorado.

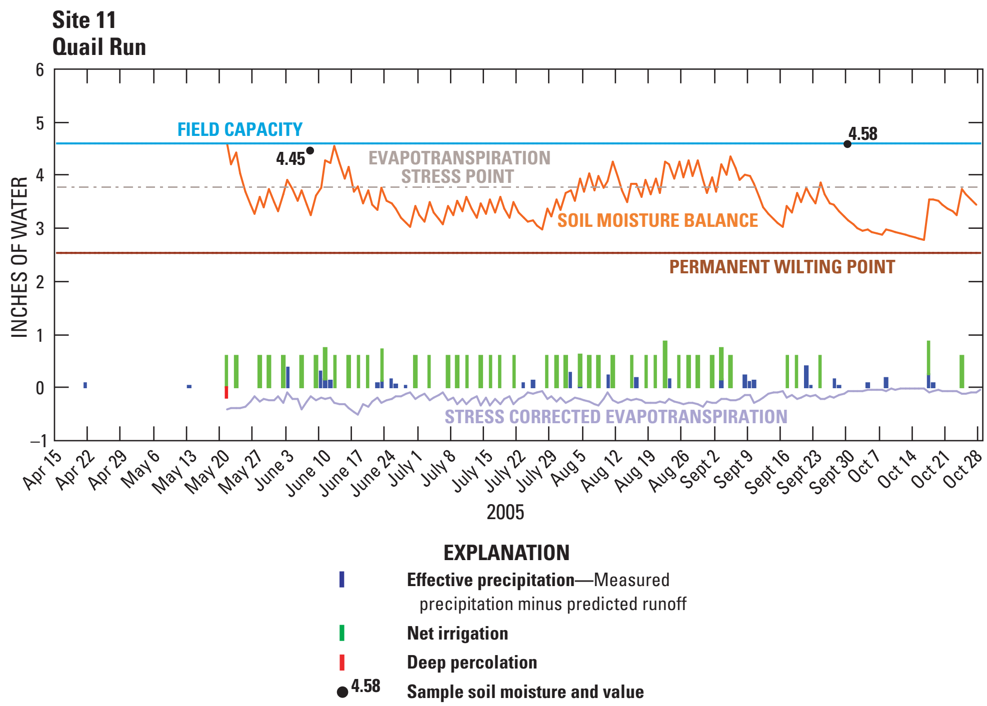


Figure A7. Soil-moisture balance for 2005 season, site 11, Grand Valley, western Colorado.

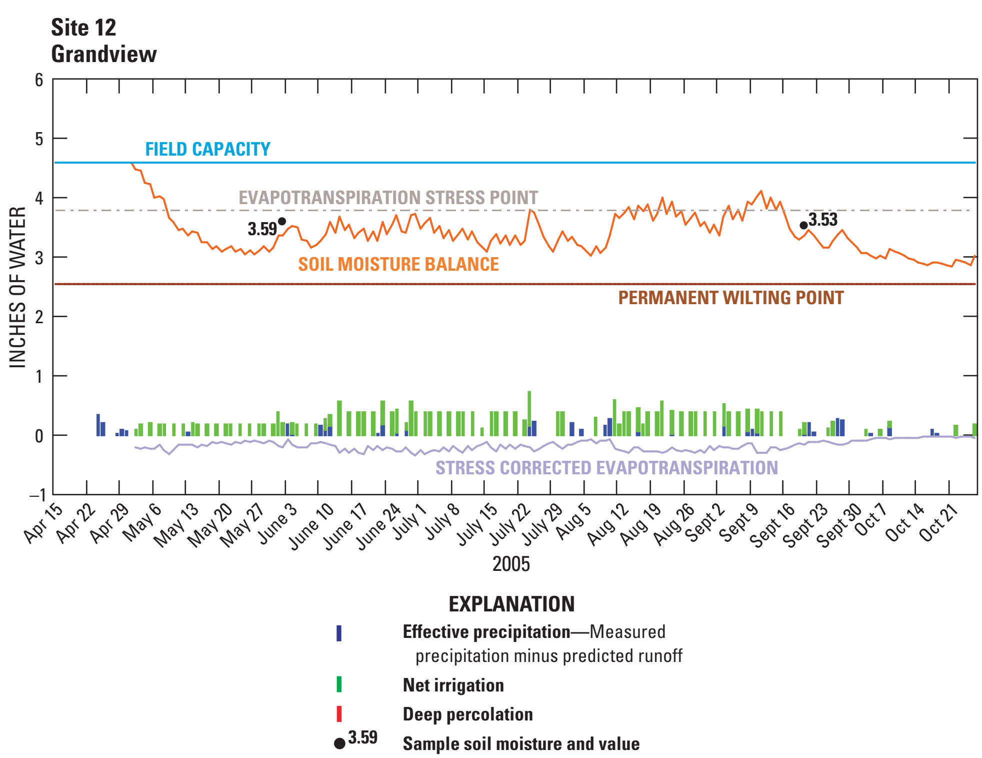


Figure A8. Soil-moisture balance for 2005 season, site 12, Grand Valley, western Colorado.

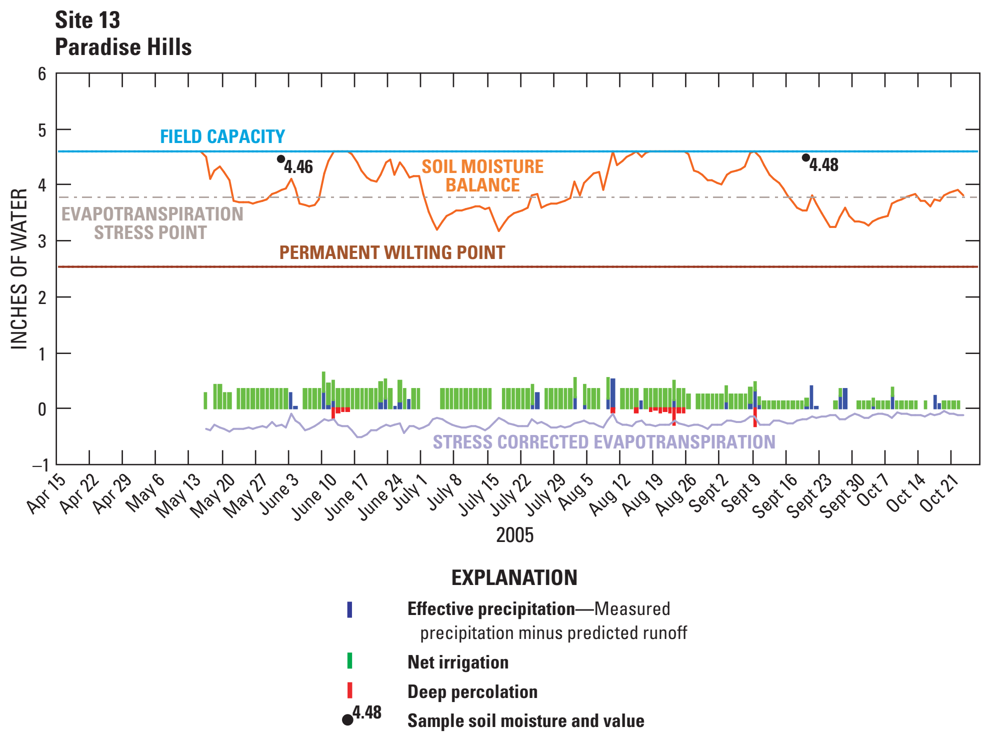


Figure A9. Soil-moisture balance for 2005 season, site 13, Grand Valley, western Colorado.

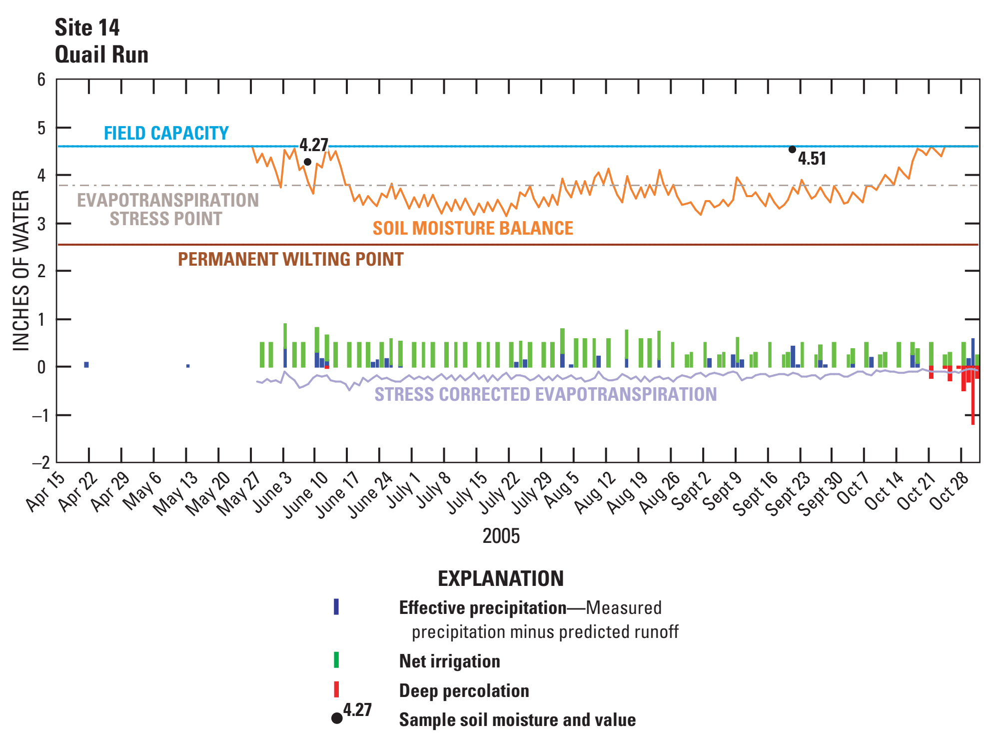


Figure A10. Soil-moisture balance for 2005 season, site 14, Grand Valley, western Colorado.

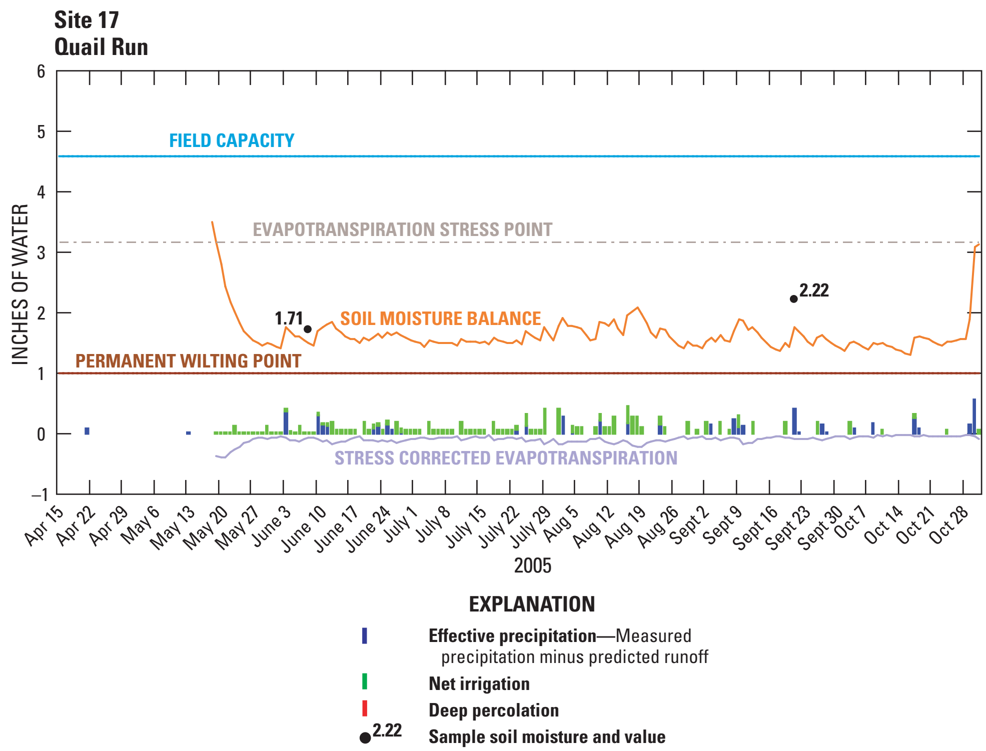


Figure A11. Soil-moisture balance for 2005 season, site 17, Grand Valley, western Colorado.

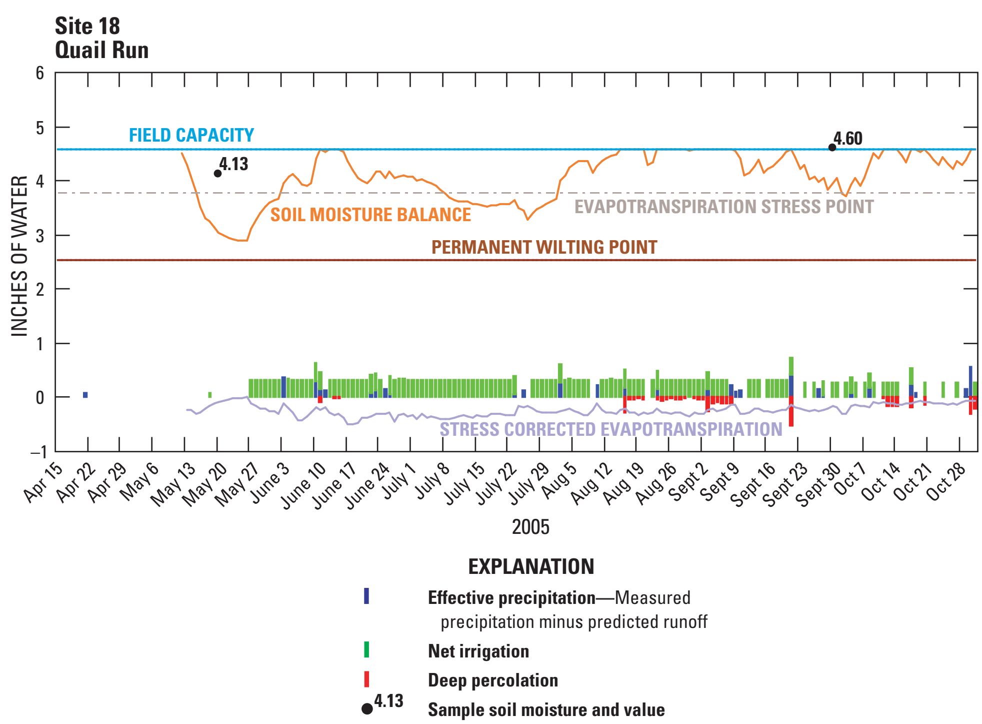


Figure A12. Soil-moisture balance for 2005 season, site 18, Grand Valley, western Colorado.

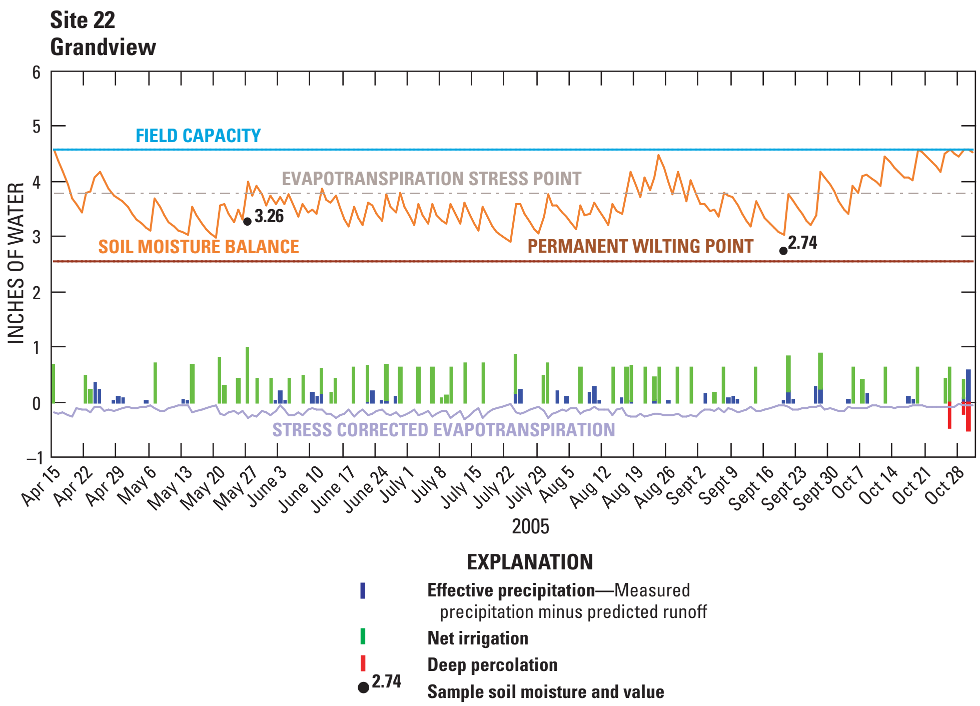


Figure A13. Soil-moisture balance for 2005 season, site 22, Grand Valley, western Colorado.

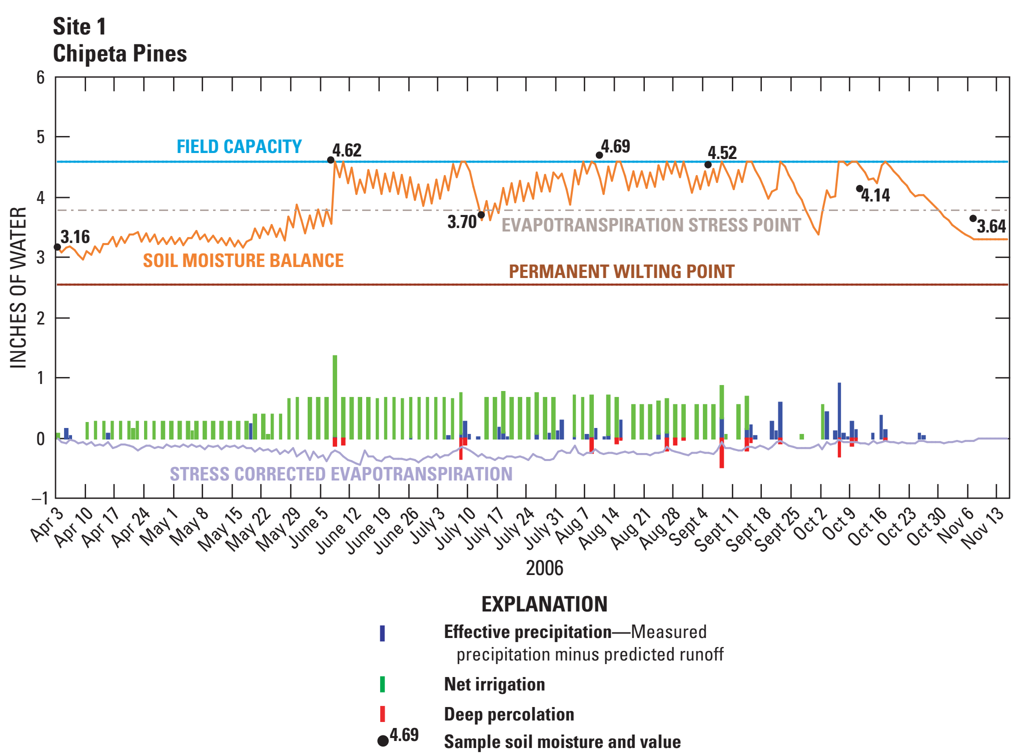


Figure A14. Soil-moisture balance for 2006 season, site 1, Grand Valley, western Colorado.

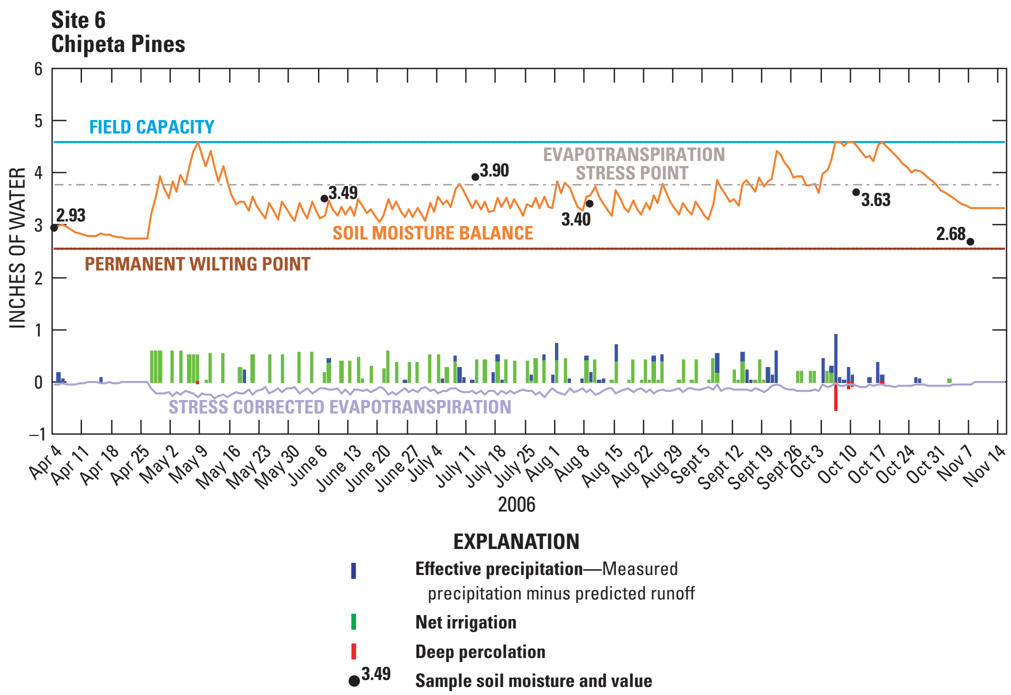


Figure A15. Soil-moisture balance for 2006 season, site 6, Grand Valley, western Colorado.

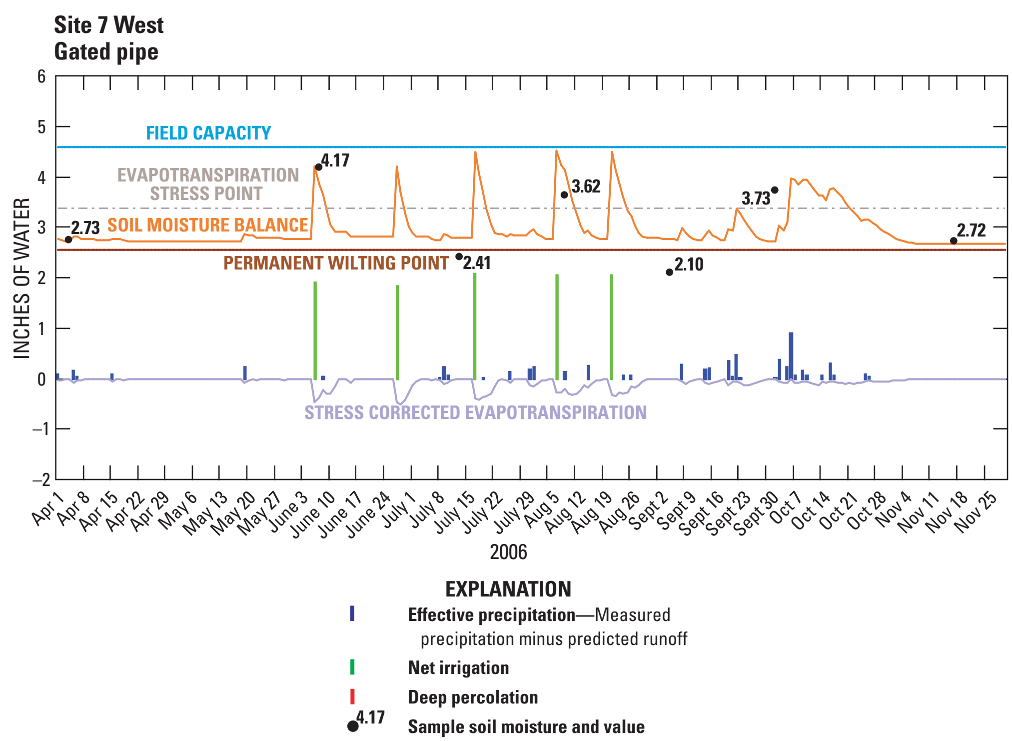


Figure A16. Soil-moisture balance for 2006 season, site 7 west, Grand Valley, western Colorado.

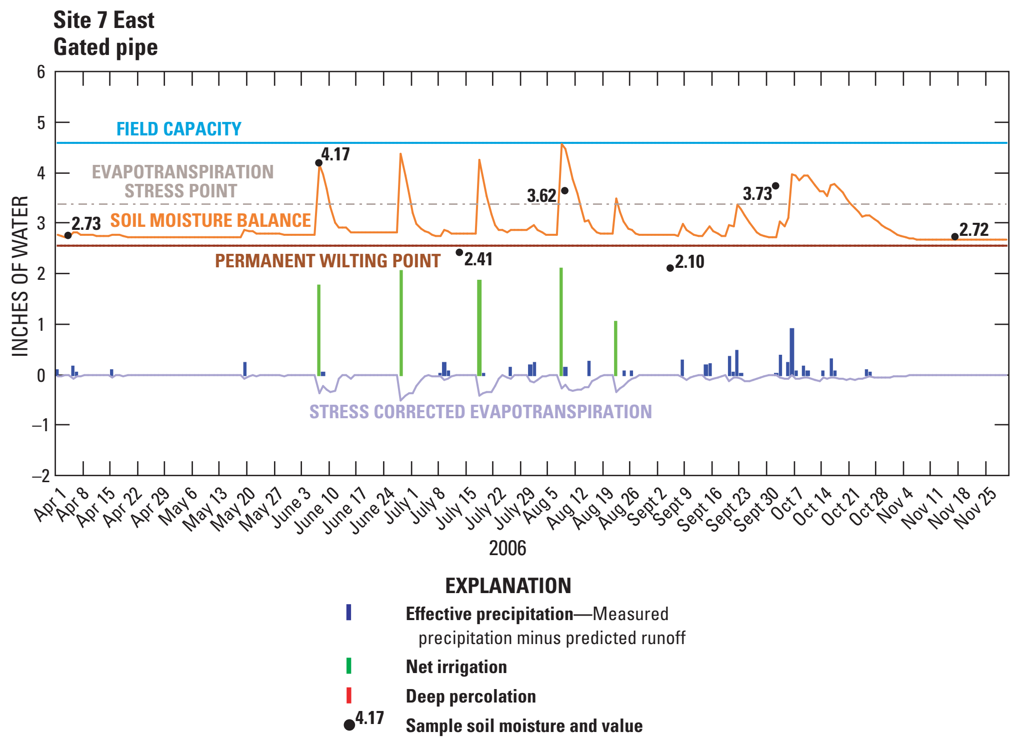


Figure A17. Soil-moisture balance for 2006 season, site 7 east, Grand Valley, western Colorado.

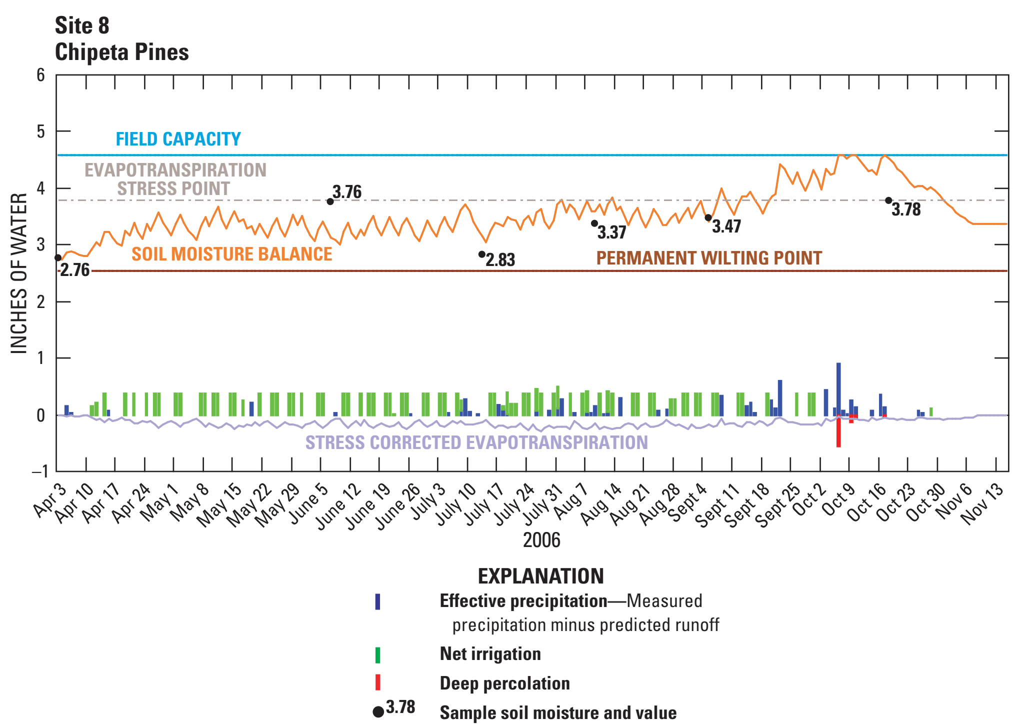


Figure A18. Soil-moisture balance for 2006 season, site 8, Grand Valley, western Colorado.

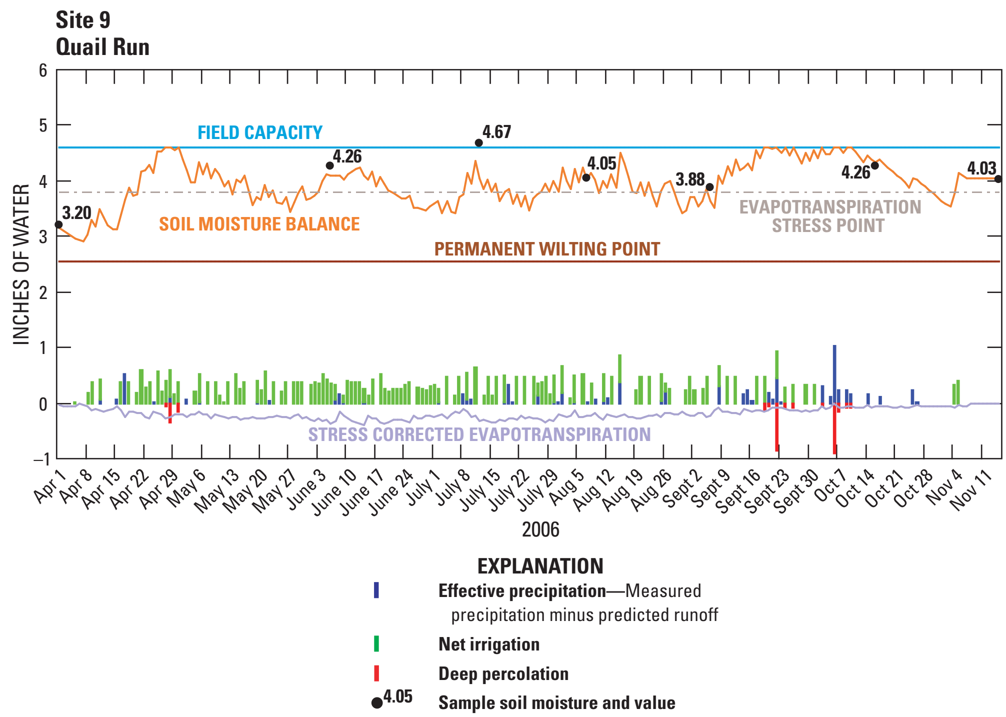


Figure A19. Soil-moisture balance for 2006 season, site 9, Grand Valley, western Colorado.

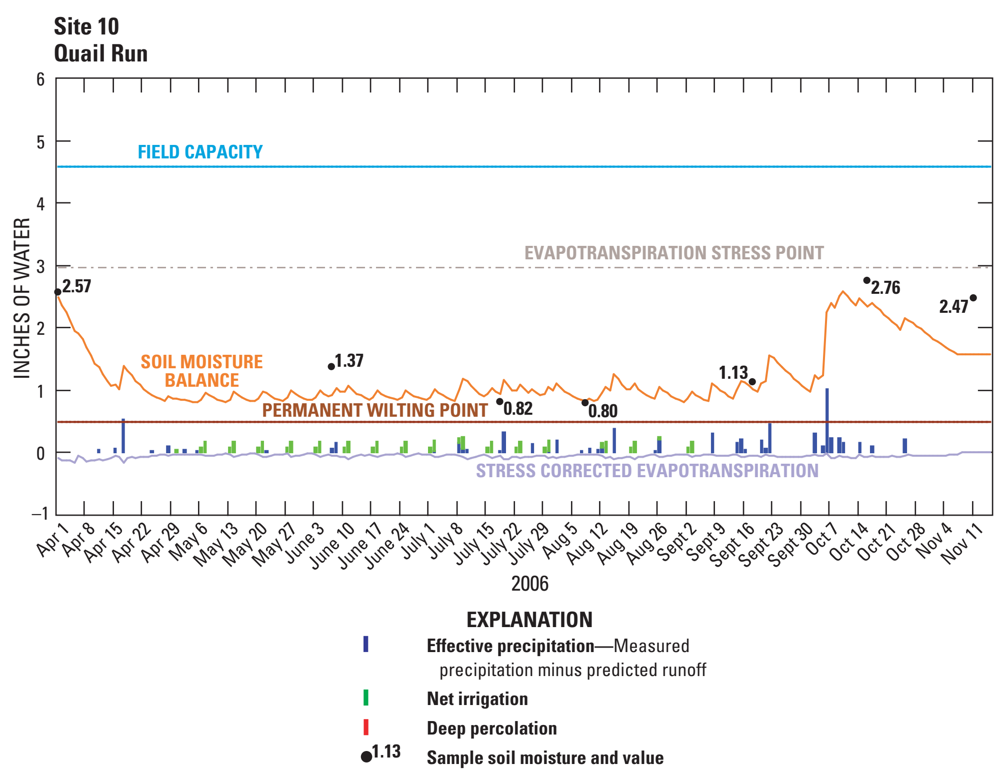


Figure A20. Soil-moisture balance for 2006 season, site 10, Grand Valley, western Colorado.

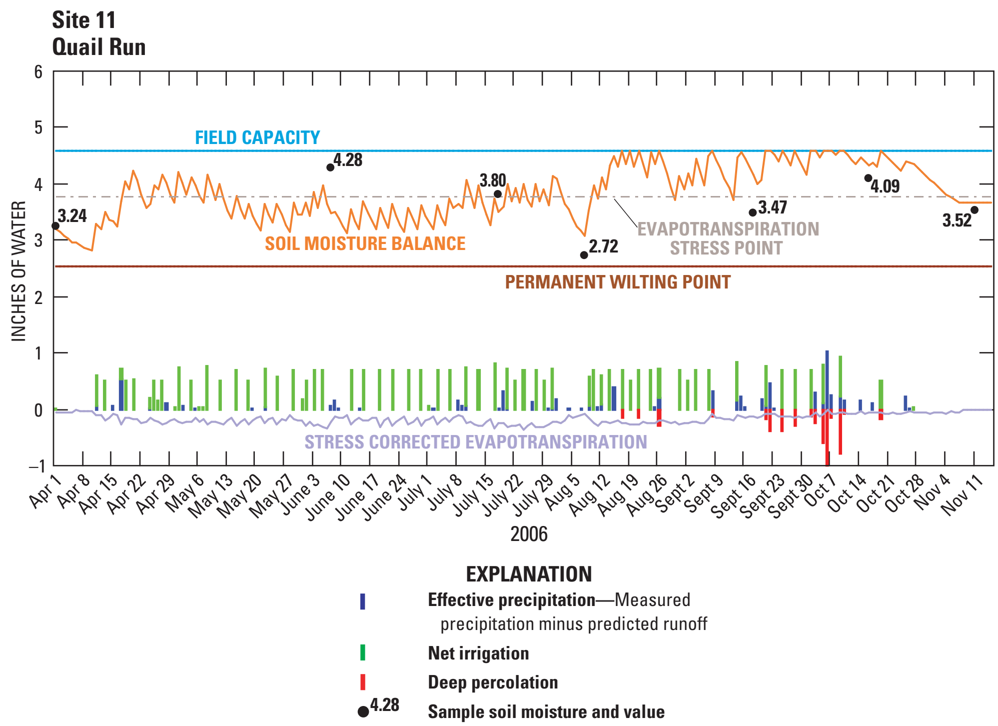


Figure A21. Soil-moisture balance for 2006 season, site 11, Grand Valley, western Colorado.

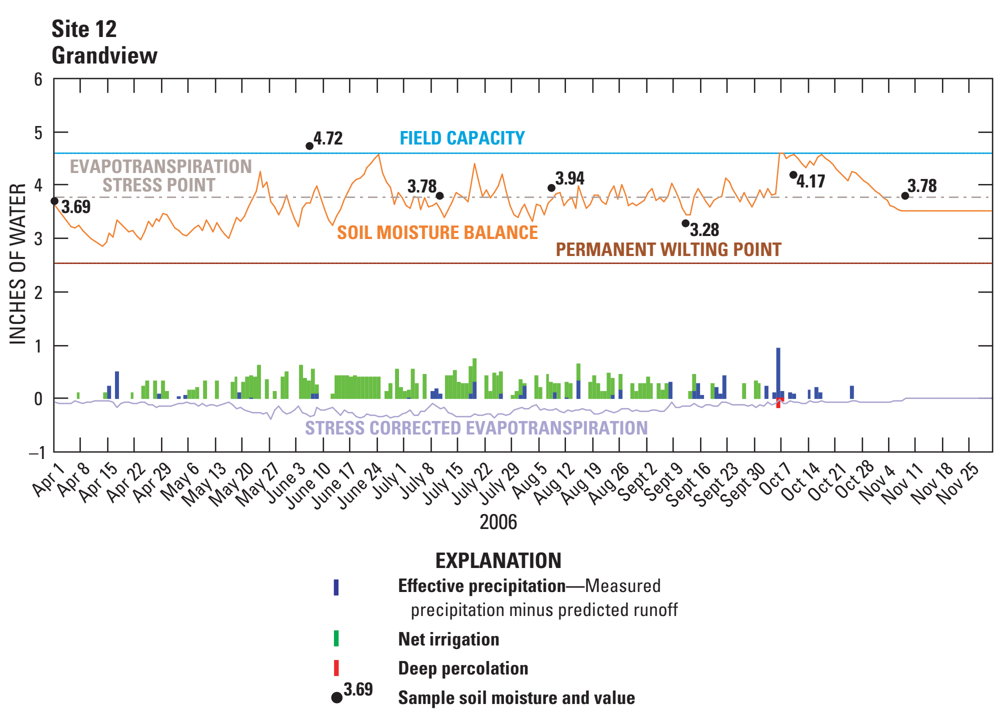


Figure A22. Soil-moisture balance for 2006 season, site 12, Grand Valley, western Colorado.

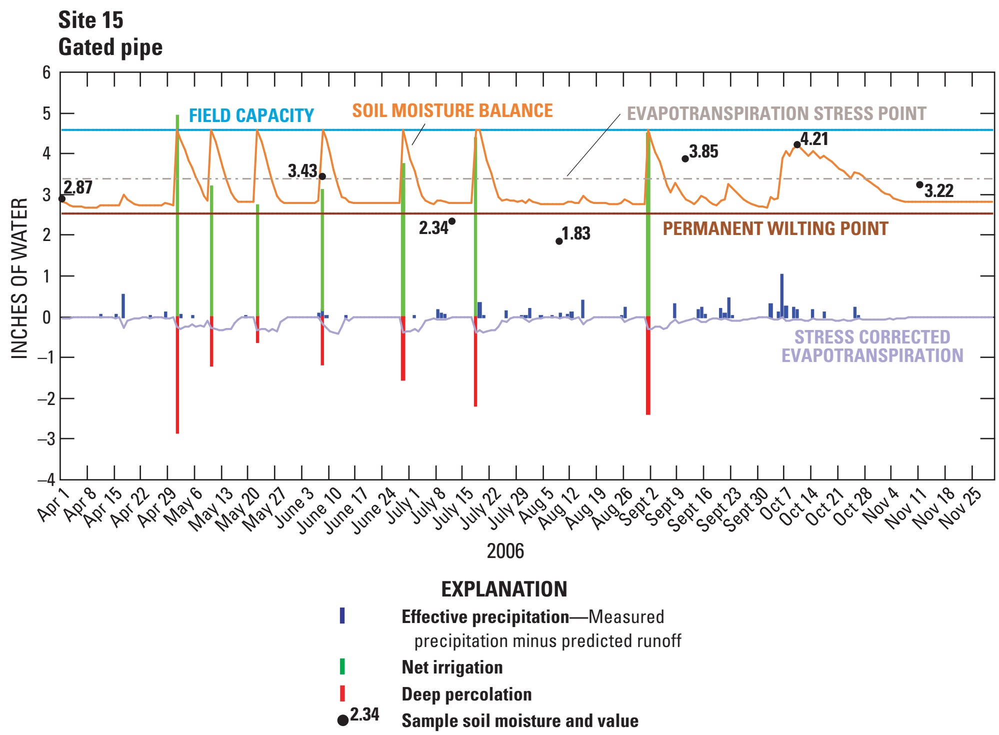


Figure A23. Soil-moisture balance for 2006 season, site 15, Grand Valley, western Colorado.

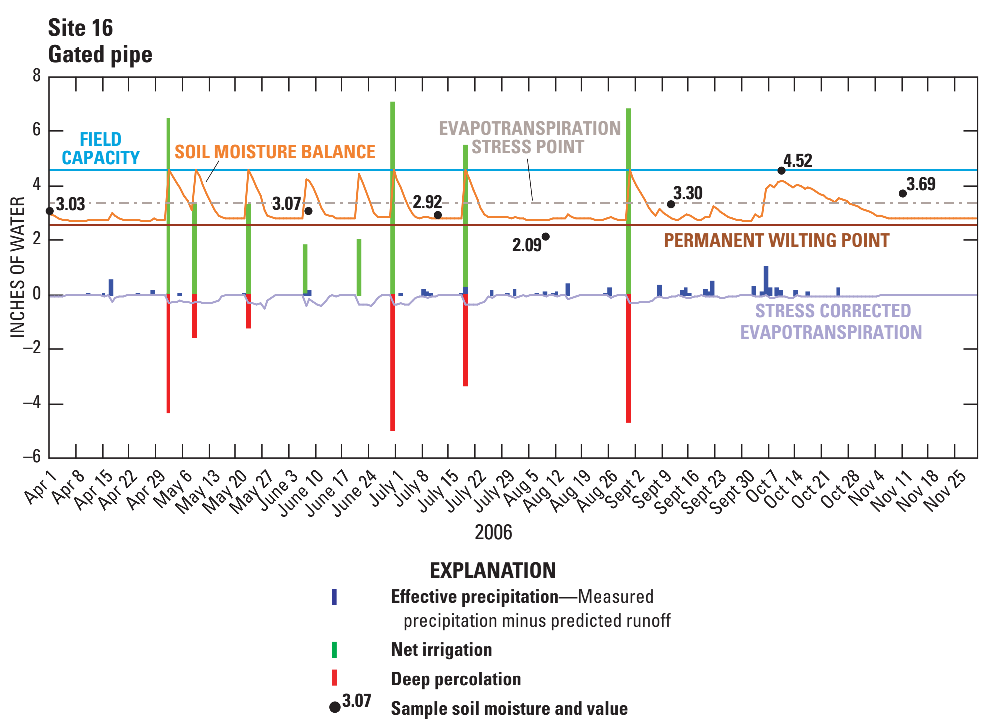


Figure A24. Soil-moisture balance for 2006 season, site 16, Grand Valley, western Colorado.

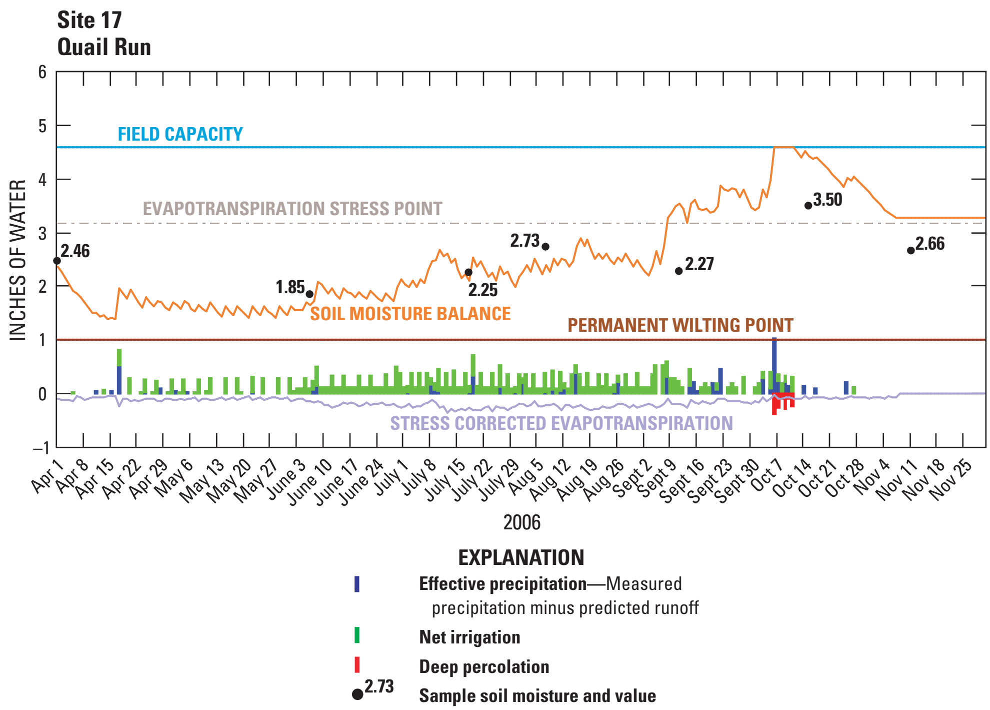


Figure A25. Soil-moisture balance for 2006 season, site 17, Grand Valley, western Colorado.

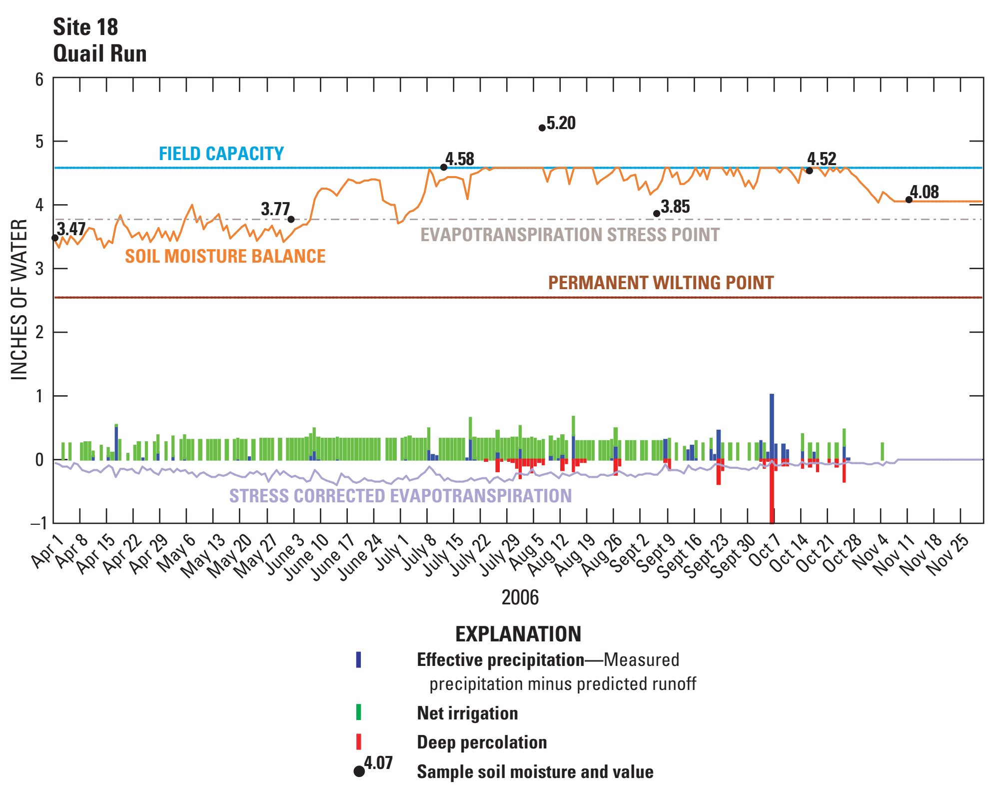


Figure A26. Soil-moisture balance for 2006 season, site 18, Grand Valley, western Colorado.

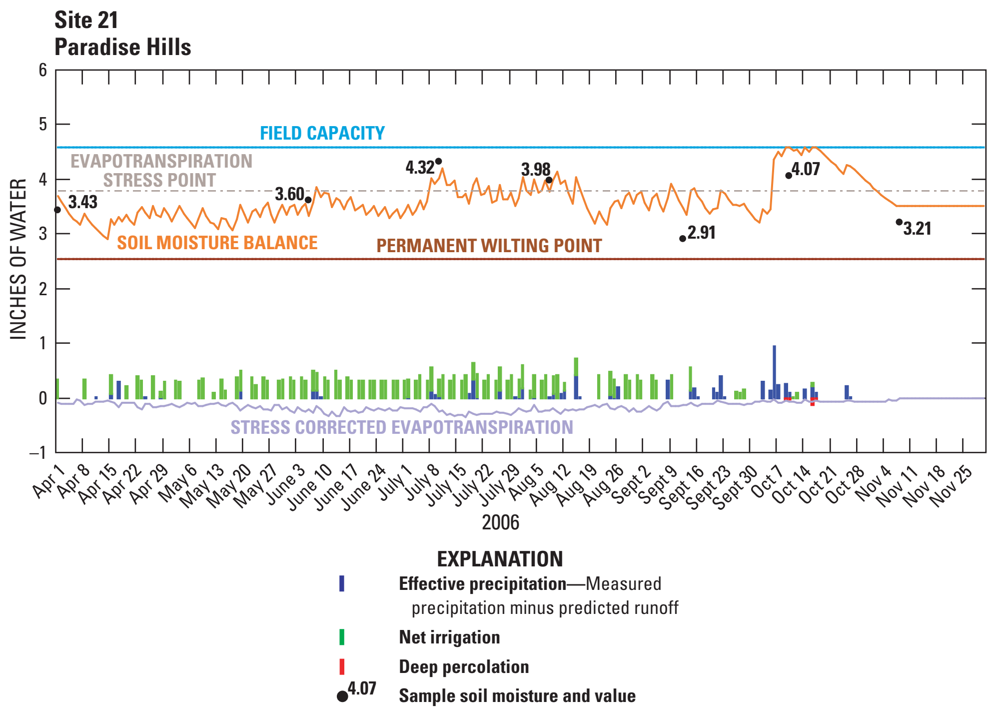


Figure A27. Soil-moisture balance for 2006 season, site 21, Grand Valley, western Colorado.

Appendix 2. Supplemental Data CD–ROM (in pocket, back of report)

The supplemental data CD–ROM contains a Microsoft® Office Excel 2003 spreadsheet with the following worksheets:

Worksheet tab name	Worksheet title
Title Page	Title Page
Daily Soil-Moisture Data	Daily Soil-Moisture Balance Data for Urban Study Sites
2005 Site Weather Data	2005 Weather Data and Sources for Urban Study Sites
2006 Site Weather Data	2006 Weather Data and Sources for Urban Study Sites
Grand Junction Coagmet 2005	Grand Junction COAGMET Daily Weather Data for 2005
Grand Junction Coagmet 2006	Grand Junction COAGMET Daily Weather Data for 2006
Orchard Mesa Coagmet 2006	Orchard Mesa COAGMET Daily Weather Data for 2006
NRCS Study Data	Natural Resources Conservation Service (NRCS) Monitoring & Evaluation (M&E) Data for All Agricultural Sites

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