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QUANTIFICATION OF DEEP PERCOLATION FROM TWO FLOOD-IRRIGATED ALFALFA FIELDS, ROSWELL BASIN, NEW MEXICO

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 98-4096

Prepared in cooperation with the

OFFICE OF THE STATE ENGINEER

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By D. Michael Roark and Denis F. Healy

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Albuquerque, New Mexico
1998

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QUANTIFICATION OF DEEP PERCOLATION FROM TWO FLOOD-IRRIGATED ALFALFA FIELDS, ROSWELL BASIN, NEW MEXICO

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Abstract

For many years water management in the Roswell ground-water basin (Roswell Basin) and other declared basins in New Mexico has been the responsibility of the State of New Mexico. One of the water management issues requiring better quantification is the amount of deep percolation from applied irrigation water. Two adjacent fields, planted in alfalfa, were studied to determine deep percolation by the water-budget, volumetric-moisture, and chloride mass-balance methods. Components of the water-budget method were measured, in study plots called borders, for both fields during the 1996 irrigation season. The amount of irrigation water applied in the west border was 95.8 centimeters and in the east border was 169.8 centimeters. The total amount of precipitation that fell during the irrigation season was 21.9 centimeters. The increase in soil-moisture storage from the beginning to the end of the irrigation season was 3.2 centimeters in the west border and 8.8 centimeters in the east border. Evapotranspiration, as estimated by the Bowen ratio energy balance technique, in the west border was 97.8 centimeters and in the east border was 101.0 centimeters. Deep percolation determined using the water-budget method was 16.4 centimeters in the west border and 81.6 centimeters in the east border. An average deep percolation of 22.3 centimeters in the west border and 31.6 centimeters in the east border was determined using the volumetric-moisture method. The chloride mass-balance method determined the multiyear deep percolation to be 15.0 centimeters in the west border and 38.0 centimeters in the east border. Large differences in the amount of deep percolation between the two borders calculated by the water-budget method are due to differences in the amount of water that was applied to each border. More water was required to flood the east border because of the greater permeability of the soils in that field and the smaller rate at which water could be applied.

INTRODUCTION

For many years water management in the Roswell ground-water basin (Roswell Basin) (fig. 1) and other declared ground-water basins in New Mexico has been the responsibility of the State of New Mexico. A declared ground-water basin is an area designated by the Office of the State Engineer for administration of ground-water rights. One water management issue requiring better quantification is the amount of deep percolation from applied irrigation water. This quantification is needed so that the Office of the State Engineer and others can better understand ground-water systems and estimate the amount of ground-water depletion in each basin. Deep percolation as defined for this study is water that percolates beyond the influence of the root and surface zone. Depletion is "that part of a withdrawal that has been evaporated, transpired, incorporated into crops or products, consumed by man or livestock, or otherwise removed from the water environment" (Wilson, 1992, p. 68). To address this issue, the U.S. Geological Survey in cooperation with the Office of the State Engineer studied two adjacent fields in the Dexter area of the Roswell Basin in southeastern New Mexico to estimate the amount of deep percolation from flood irrigation. This report was prepared in cooperation with the Office of the State Engineer.

Purpose and Scope

This report presents the data-collection and interpretation methods used in a study of deep percolation in two alfalfa fields in the Roswell Basin. Two neutron-moisture-meter access holes were

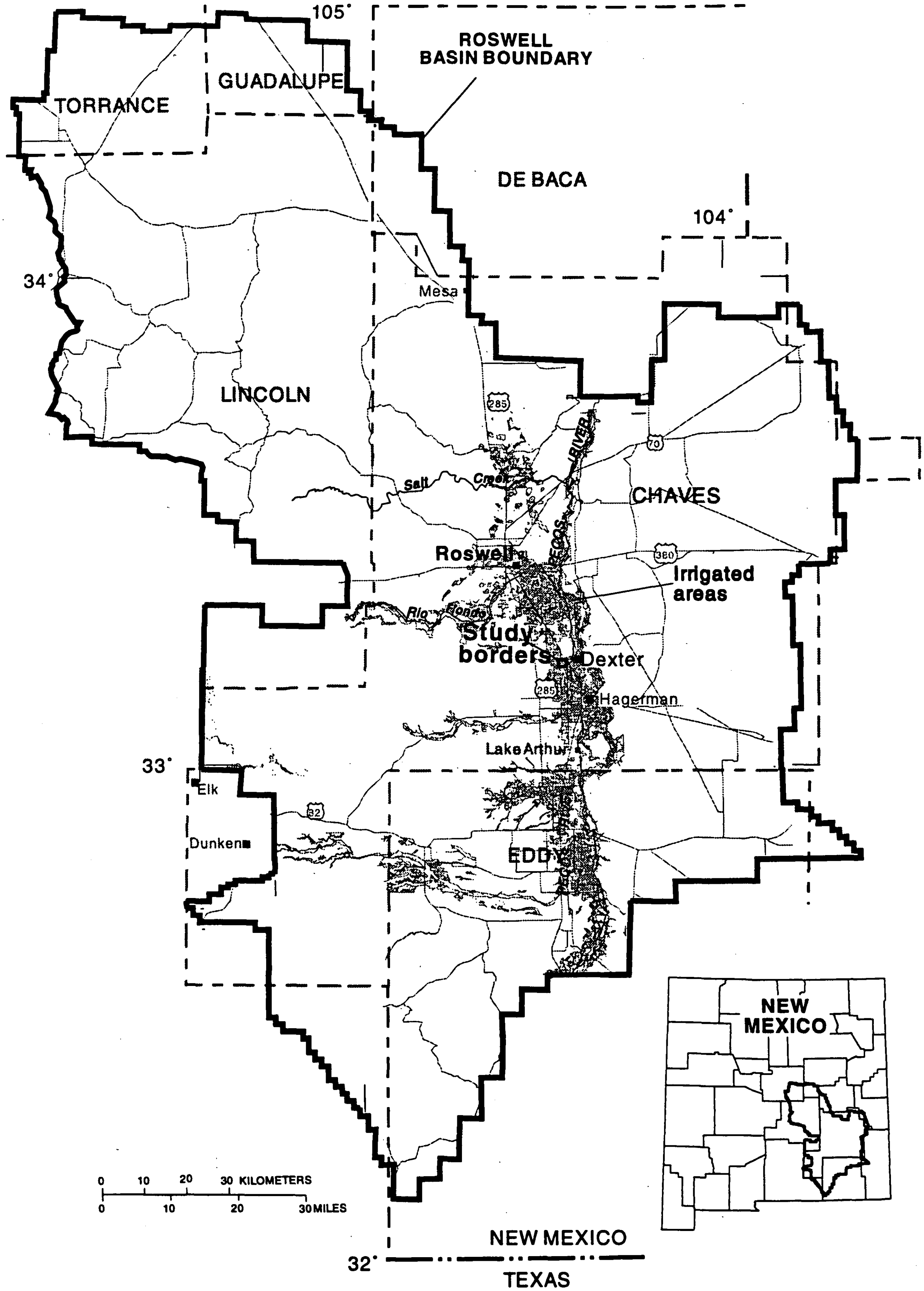

Figure 1.--Distribution of irrigated areas (shaded), 1991, and location of study borders and Roswell Basin, New Mexico.

installed during the summer of 1995, and a reconnaissance of soil-moisture movement was completed. The remaining neutron-moisture-meter access holes and all other equipment were installed in the spring of 1996. Data collection ended in October 1996. Three methods were used to determine the amount of deep percolation. The error associated with the interpretation methods and the relation of the study findings to the entire Roswell Basin were analyzed.

Description of Study Area

The Office of the State Engineer designated parts of the Roswell Basin a "declared ground-water basin" as early as 1931. The declared ground-water basin has been expanded through the years to its present extent of 13,081 square kilometers (Peggy Barroll, Office of the State Engineer, written commun., April 1997).

The land adjacent to the Pecos River is used for irrigated farming. Although surface water is used for irrigation in part of the basin, ground water is the primary source in the Roswell Basin. The main source of ground water for irrigation is the deep San Andreas aquifer, although the shallower water-table aquifer is becoming increasingly important. The amount of ground water used for irrigation is metered.

Of the 13,081 square kilometers of land in the basin, 365 square kilometers were irrigated in 1994 (Lansford and others, 1995). Most farming in the basin is on the west side of the Pecos River (fig. 1). Major crops in the basin are alfalfa, cotton, and corn (Lansford and others, 1995). In an average year about 60 percent of the cropland in production in the basin is planted in alfalfa. About 70 percent of this alfalfa is flood irrigated.

The study was conducted in two adjacent fields (fig. 2). The fields are orientated perpendicular to each other: the top of the west field is on the west side and the top of the east field is on the south side. The top of the field is the side where water is applied. The west field is divided into 24 subplots, called "borders," which run the length of the field and generally are about 31.7 meters wide and 230.1 meters long. The east field is divided into 10 borders about 31.7 meters wide and 263.6 meters long. A representative border was selected in each field for this study. The west field study border totals 7.29 square hectometers, and the east field study border totals 8.36 square hectometers. The borders are bounded by dirt berms on each side, which help ensure that water applied to the field will reach the entire length of the field. Both fields have been leveled to achieve better irrigation efficiencies. Water to irrigate the two fields originates from a well completed in the San Andreas aquifer.

Both study fields were planted with common alfalfa, the west field during 1993 and the east field during 1994. Usually, alfalfa is grown for 5 to 6 years before the field is plowed and replanted. The amount of water used by alfalfa changes from year to year depending on the maturity of the alfalfa. When alfalfa is first planted, its water use is high; as it matures, water use declines. The two study fields were chosen for the middle age of their alfalfa.

Climate

The climate of the Roswell Basin is characterized by mild winter temperatures, hot summer temperatures, small amounts of precipitation, and moderate to strong winds. For 1972-92 at Roswell Industrial Air Park, 20 kilometers from the study fields, the average January temperature was 11.7 degrees Celsius and the average June temperature was 34 degrees Celsius (National Oceanic and Atmospheric Administration, 1998). The average monthly temperature during the growing season (May to September) was 32 degrees Celsius for 1972-92. Figure 3 shows the maximum, minimum, and average monthly temperatures at Roswell Industrial Air Park for 1972-92.

Most of the annual precipitation falls in the summer as the result of summer thunderstorm activity. Average annual precipitation in the Roswell area during 1972-92 was 35.6 centimeters. Average monthly precipitation during the growing season was 4.9 centimeters for 1972-92. Figure 4 shows the maximum, minimum, and average monthly precipitation at Roswell Industrial Air Park for 1972-92.

Hydrogeology and Soils

The Pecos River (fig. 1) is the only major stream in the Roswell Basin. Streamflow in the river is regulated for irrigation in New Mexico and for deliveries of Pecos River Compact water to Texas.

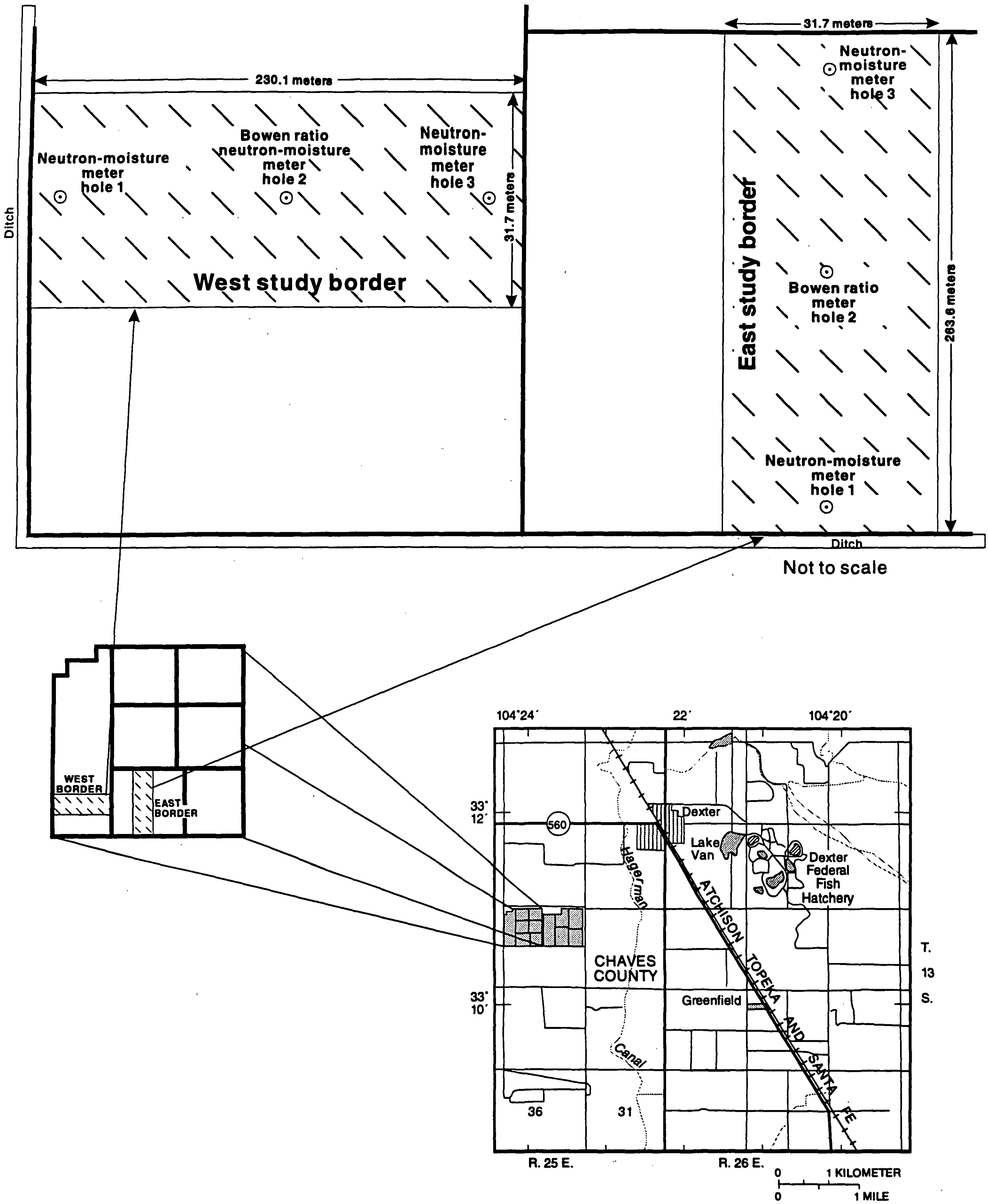

Figure 2.--Study borders and location of equipment, Roswell Basin, New Mexico.

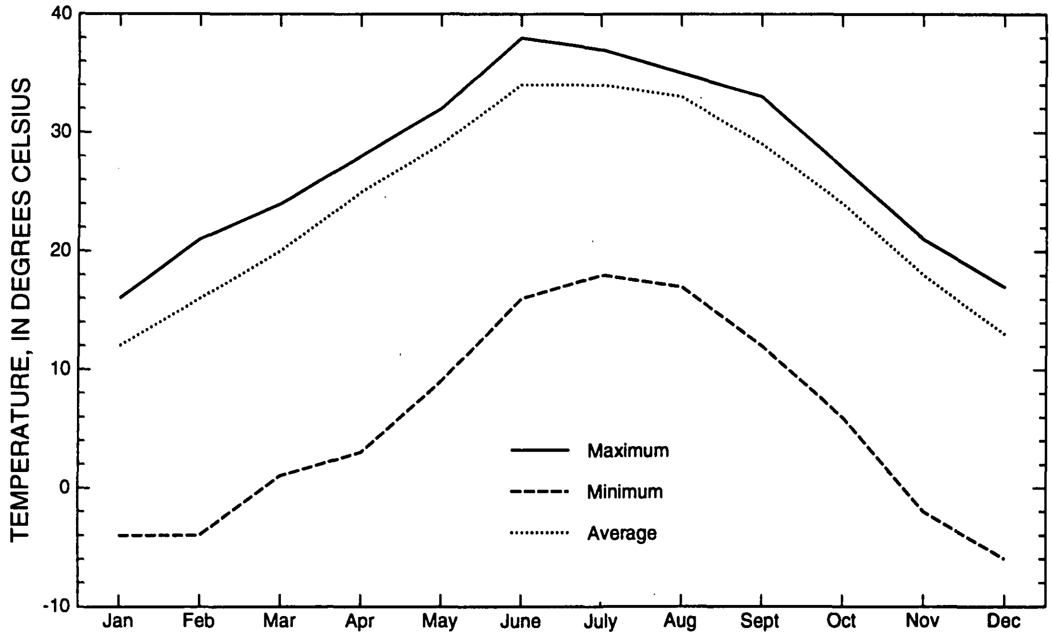

Figure 3.--Maximum, minimum, and average monthly temperatures at Roswell Industrial Air Park, New Mexico, 1972-92.

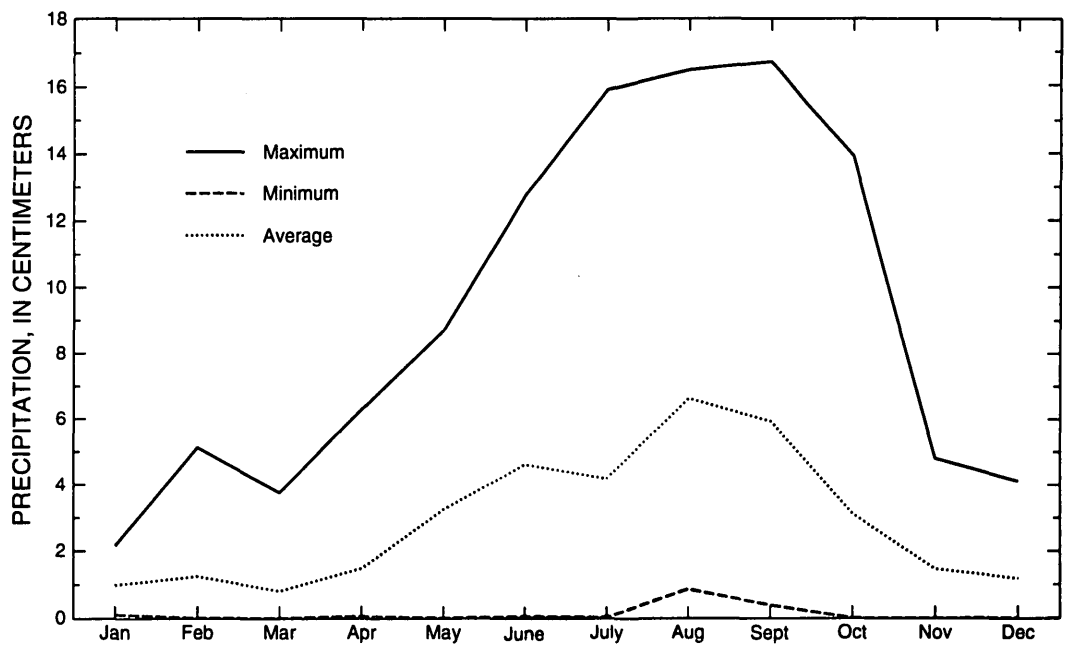

Figure 4.--Maximum, minimum, and average monthly precipitation at Roswell Industrial Air Park, New Mexico, 1972-92.

Two major aquifers in the basin are the shallow, unconfined water-table aquifer and the deeper San Andreas aquifer. Depth to the water-table aquifer is about 36.57 meters in the study-field area. Recharge enters the San Andreas aquifer in the mountains and at streams on the eastern flanks of the mountains on the west side of the basin and moves to the center of the basin, near the Pecos River. The San Andreas aquifer is not a confined system until near the center of the basin. Most discharge from the San Andreas aquifer consists of water pumped for agriculture.

Most intensive agriculture in the Roswell Basin is located near the river in either Reakor or Reeves series soils. Although the two soil series are very similar, the Reeves series contains more gypsum. Permeability of both soils generally is the same, as shown in Hodson and others (1980). Soils in the two study fields are Reakor series, which are deep, well-drained soils. Typically, in the Reakor series,

> "*In a representative profile the surface layer is a brown and light brown loam about 7 inches thick. The subsoil is a light brown heavy loam and clay loam about 23 inches thick. The substratum is pink clay loam high in content of lime to a depth of 65 inches or more. The soil profile is moderately calcareous in the surface layer and strongly calcareous below*" (Hodson and others, 1980, p. 36).

Particle-size distribution was determined at intervals in two sets of cores from neutron-moisture-meter access holes at west study border hole 1 and east study border hole 1 (fig. 2). The distribution with depth is shown in table 1 and in figures 5 and 6.

Analysis of the cores shows that the soils are heterogeneous and contain significant layering. Generally, the particle sizes in the west study border core are predominantly silt above 300 centimeters and clay below. The amount of sand in the west study border core diminishes with depth from about 30 percent near the surface to about 10 percent below 300 centimeters. The east study border core contains a fairly even distribution of sand, silt, and clay throughout the core except between 200 and 300 centimeters, where silt is predominant. Layering can affect the vertical movement of water.

Acknowledgments

The study could not have been completed without the cooperation and information provided by many residents of the Roswell Basin. Lonie Ashcraft (Natural Resources Conservation Service) provided information on soils and types of farming techniques used in the basin. Claude Hill of Bogle Farms provided the study fields, cooperation on water schedules, and knowledge of farming techniques.

DATA-COLLECTION METHODS AND DATA SUMMARY

Irrigation and Precipitation

In the Roswell Basin, irrigation water is delivered to crops by either sprinkler or one of several types of flood irrigation. The method used to deliver most water to alfalfa in the Roswell Basin and the method used in this study is siphon-type flood irrigation. For this method, water is siphoned through a set of 7.6-centimeter pipes from a ditch at the top of the field into borders in the field. During this study, 25 to 35 irrigation pipes were used in each border to deliver water to the field.

Water for the study fields is pumped from a well completed in the San Andreas aquifer into a storage pond. After the pond has filled, water is diverted to a small irrigation ditch located along the top of each field. The ditches leading to the study fields are concrete lined, as are many ditches in the Roswell Basin, to reduce the amount of delivery losses. Water is siphoned for the period of time needed to cover each entire border. The amount of water entering the soil is unevenly distributed along the length of the border. Water has more time to enter the soil profile near the top of the border than at the bottom.

The amount of irrigation water applied to the study borders was measured during each irrigation event using standard U.S. Geological Survey methods. The flow of water in the concrete-lined ditch was measured upstream and downstream from the study border several times during the irrigation event and re-measured whenever the number of discharge pipes changed. The error associated with the measurements was plus or minus 10 percent of the measurement. The amount of water applied to each study border was calculated by converting the difference of the discharge measurements upstream and downstream to cubic meters per minute, then multiplying the conversion by the number of minutes that the water was applied. Table 2 shows the dates that water was applied, the amount of water applied per unit area of the border, and the total amount applied.

Table 1.--Laboratory-determined particle-size distribution with depth in study borders, Roswell Basin, New Mexico

[<, less than; mm, millimeters; --, no data]

Depth below land surface (centimeters)	Clay (<0.004 mm) (percent)	Silt (0.004 to <0.063 mm) (percent)	Sand (0.063 to 2 mm) (percent)
	West study border hole 1		
30	25.0	45.8	29.2
61	--	--	--
91	37.7	39.0	23.3
122	--	--	--
152	26.2	56.1	17.7
183	--	--	--
213	5.3	63.5	31.2
244	--	--	--
274	19.3	48.6	32.1
305	53.3	33.0	13.7
335	58.6	30.8	10.6
366	67.8	19.6	12.6
396	64.1	28.2	7.7
423	64.7	26.8	8.5
457	58.4	30.3	11.3
488	64.7	28.8	6.5
518	14.0	60.2	25.8
549	37.6	56.3	6.1
579	57.1	35.3	7.6
610	39.5	49.5	11.0
	East study border hole 1		
30	23.0	31.8	45.2
61	39.7	30.7	29.6
91	52.9	21.9	25.2
122	29.3	17.2	53.5
152	18.7	35.3	46.0
183	26.6	32.4	41.0
213	7.0	74.9	18.1
244	5.9	63.1	31.0
274	41.1	50.6	8.3
305	21.6	47.7	30.7

Table 1.--Laboratory-determined particle-size distribution with depth in study borders, Roswell Basin, New Mexico--Concluded

Depth below land surface (centimeters)	Clay (<0.004 mm) (percent)	Silt (0.004 to <0.063 mm) (percent)	Sand (0.063 to 2 mm) (percent)
335	24.9	37.3	37.8
366	40.5	34.3	25.2
396	45.9	31.9	22.2
423	62.3	21.7	16.0
457	31.9	50.8	17.3
488	28.8	21.9	49.3
518	30.1	19.0	50.9
549	33.0	14.4	52.6
579	32.6	28.9	38.5
610	65.6	24.9	9.5

Table 2.--Date, amount of water applied per unit area of the study border, and total amount of irrigation water applied to study borders, Roswell Basin, New Mexico

Date	Border	Water applied per unit area (centimeters)	Water applied, total (cubic meters)
4/17/96	West	32.07	2,339.52
4/18/96	East	57.39	1,696.54
4/19/96	East	15.47	1,292.60
5/6/96	West	17.41	1,270.00
5/9/96	East	52.53	1,339.66
5/10/96	East	19.43	1,623.90
6/6/96	East	20.95	1,750.82
6/8/96	West	15.87	1,157.87
7/8/96	East	64.48	4,912.49
7/10/96	West	26.25	1,104.77
8/14/96	East	18.82	1,572.85
8/14/96	West	15.34	1,118.97

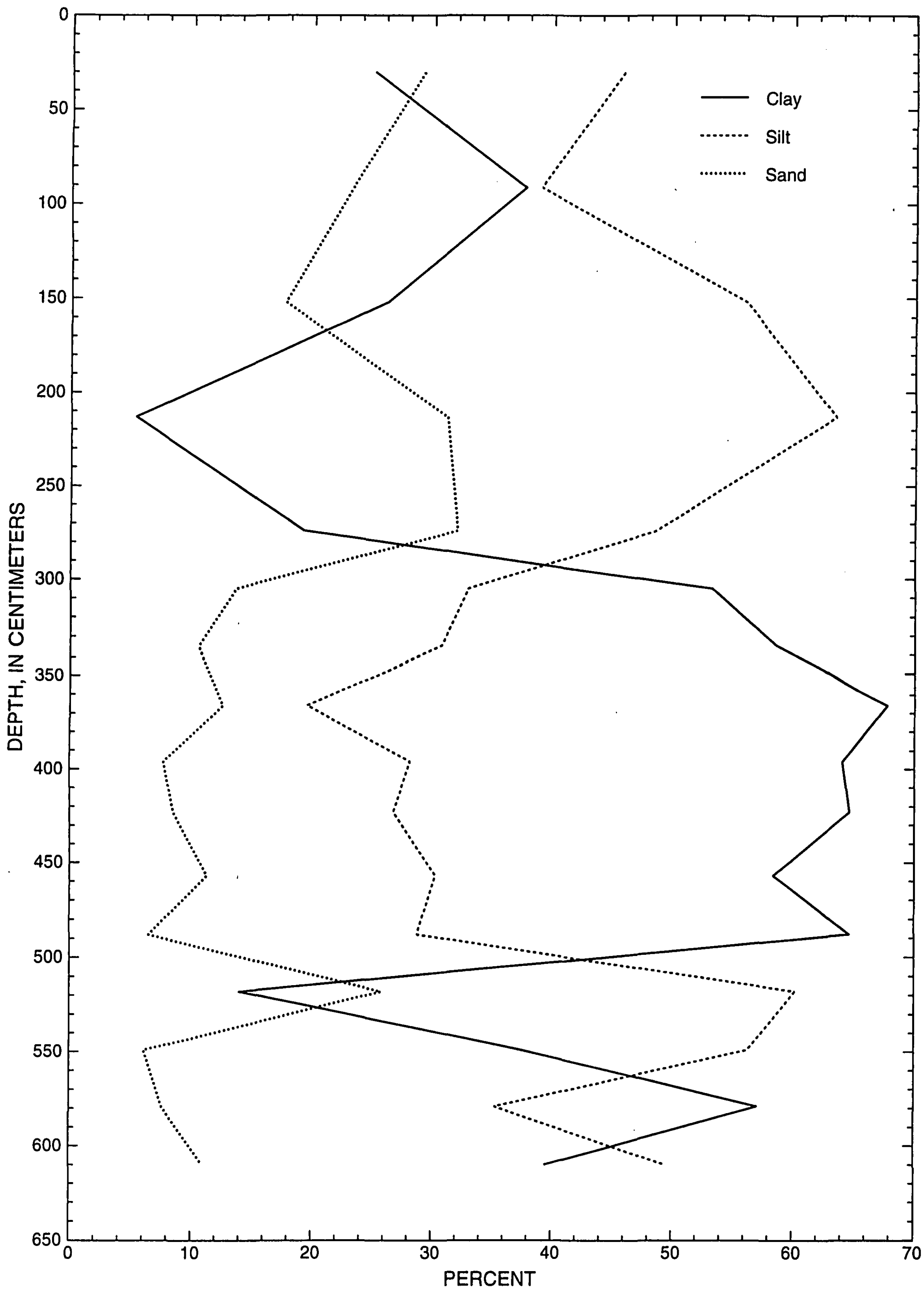

Figure 5.--Particle-size distribution with depth in west study border hole 1, Roswell Basin, New Mexico.

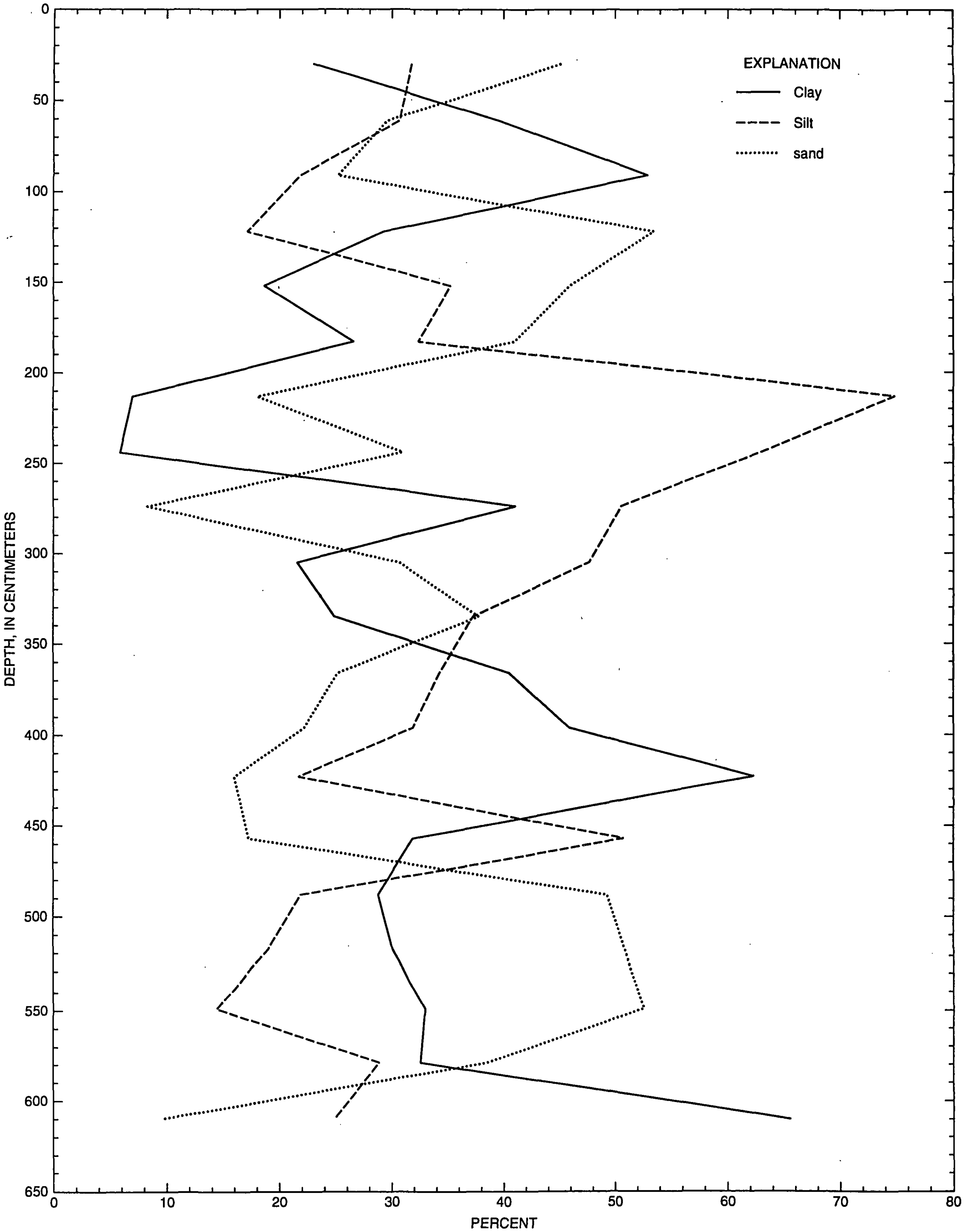

Figure 6.--Particle-size distribution with depth in east study border hole 1, Roswell Basin, New Mexico.

The average time of application of water to the borders ranged from 2.0 to 8.5 hours at the west study border and from 2.9 to 13.5 hours at the east study border. The wide range in time that was needed to irrigate the borders was due to two main variables: the permeability at the soil surface and the amount of time left in the day to water. Permeability is related to the amount of clay at the surface and the antecedent moisture at the surface. In both study borders the fastest watering times were just after a large rain that saturated the soil surface. The longer time needed to water the east study border was due to the size of the irrigation pond and the time of day. The pond was too small and could not store enough water to allow a full-ditch delivery after midday, and during several irrigation events irrigation was started in the afternoon when the ditch carried only one-half the volume of water as in the morning. Also, the water was shut off at 5:00 p.m. in the middle of irrigation and restarted again at 6:00 a.m.; therefore, the top end of the border had to be rewetted.

The timing and amount of precipitation that fell in the area of the study borders were recorded using a tipping-bucket rain gage and digital recorder placed between the two study borders. The accuracy of the precipitation data was dependent on the amount of wind and the amount of precipitation but the error in measurement is estimated to be less than 5 percent of the measurement. Figure 7 shows the timing and daily amounts of precipitation. The total amount of precipitation that fell during the irrigation season was 21.9 centimeters.

Evapotranspiration

Evapotranspiration was estimated using the Bowen ratio energy balance technique (BREB) (Tanner, 1960). This technique assumes one-dimensional vertical flux and comparatively small photosynthesis and other plant energy uptakes. The surface-energy balance is:

$$R_n - G - H - LE = 0 \tag{1}$$

where R_n is net radiation, in watts per square meter;
G is soil heat flux, in watts per square meter;
H is sensible heat-flux density, in watts per square meter; and
LE is latent heat-flux density, in watts per square meter.

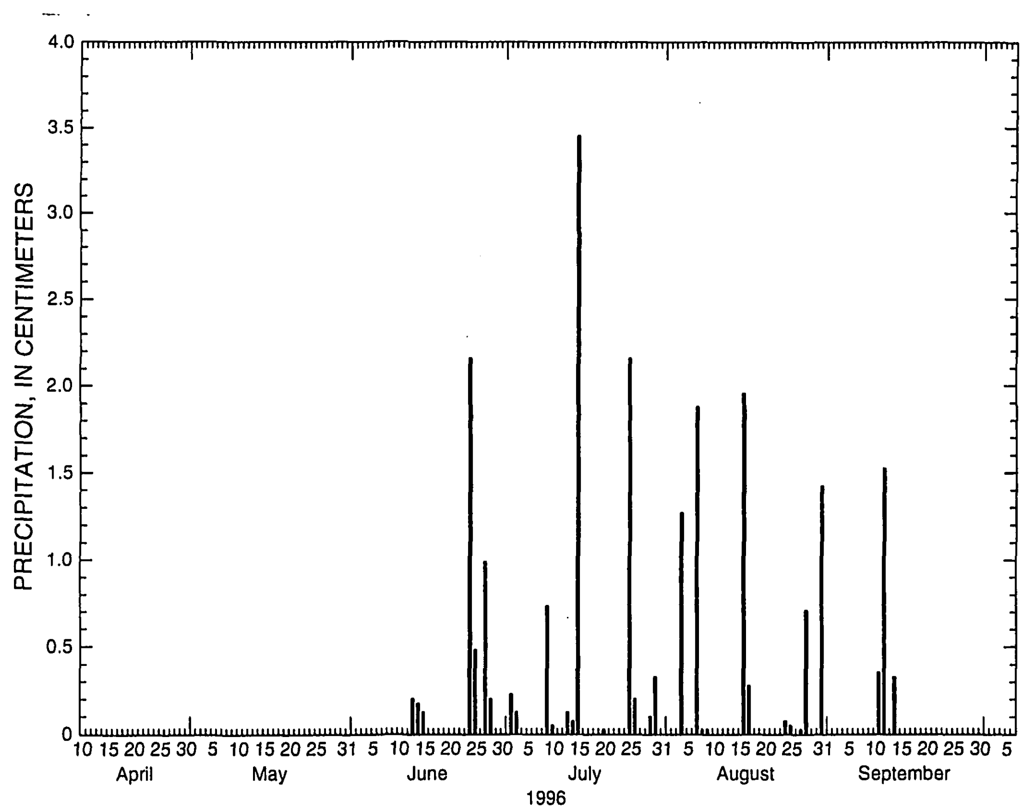

Figure 7.--Measured daily precipitation on study borders, Roswell Basin, New Mexico, 1996.

Net radiation was measured using a calibrated net radiometer located 1 meter above the soil surface. The soil heat flux was calculated from measurements made by two sets of soil heat-flux plates 8 centimeters deep and by two sets of soil thermocouples 2 and 4 centimeters deep. The soil heat flux was calculated using the equation:

$$G = \frac{FX1 + FX2}{2} + \Delta S \qquad (2)$$

where $FX1$ is soil heat flux at plate 1, in watts per square meter;

$FX2$ is soil heat flux at plate 2, in watts per square meter; and

ΔS is heat stored from 0 to 8 centimeters, in watts per square meter.

The heat stored between the soil surface and the heat-flux plates is calculated by:

$$\Delta S = \frac{dT_s \cdot d_{fp} \cdot (\rho_b \cdot (c_r + \theta \cdot c_w))}{dt} \qquad (3)$$

where dT_s is change in soil temperature, in degrees Celsius;

d_{fp} is depth of soil heat-flux plate, in meters;

ρ_b is bulk density, in kilograms per cubic meter;

c_r is specific heat of dry soil, in joules per kilogram degree Celsius;

θ is soil water content, in percent;

c_w is specific heat of water, in joules per kilogram degree Celsius; and

dt is change in time, in seconds.

The following equation from eddy diffusion theory (Hillel, 1982) gives the sensible heat-flux density:

$$H = K_h \cdot \rho_a \cdot c_p \cdot \frac{dT}{dz} \qquad (4)$$

where K_h is eddy diffusion coefficient for heat transport, in square meters per second;

ρ_a is air density, in grams per cubic meter;

c_p is heat capacity of air, in joules per kilogram degree Celsius; and

$\frac{dT}{dz}$ is temperature gradient in direction z.

The latent heat-flux density is given by:

$$LE = K_v \cdot \lambda \cdot \frac{d\rho_v}{dz} \qquad (5)$$

where K_v is eddy diffusion coefficient for vapor transport, in square meters per second;

λ is latent heat of vaporization, in joules per gram; and

$\frac{d\rho_v}{dz}$ is vapor-density gradient in direction of flux.

BREB uses the ratio of the sensible heat-flux density and the latent heat-flux density known as the Bowen ratio (Bowen, 1926):

$$\beta = \frac{H}{LE} = \frac{K_h \cdot \rho_a \cdot c_p \cdot \frac{dT}{dz}}{K_v \cdot \lambda \cdot \frac{d\rho_v}{dz}} \qquad (6)$$

where β is the Bowen ratio.

If K_h and K_v can be assumed to be equal, and finite-difference approximations of the temperature and vapor-density gradients are made, then equation 6 reduces to:

$$\beta = \gamma \cdot \frac{\Delta T}{\Delta \rho_v} \qquad (7)$$

where γ is the psychrometer constant, in grams per cubic meter per degree Celsius;

ΔT is the difference in temperature at two heights, in degrees Celsius; and

$\Delta\rho_v$ is the difference in vapor density at two heights, in grams per cubic meter.

The psychrometer constant is a function of temperature. The equation for it is:

$$\gamma = \frac{\rho_a \cdot c_p}{\lambda}. \tag{8}$$

The Bowen ratio is substituted into the surface-energy balance (eq. 1) to give the equation for latent heat-flux density:

$$LE = \frac{R_n - G}{1 + \beta}. \tag{9}$$

If both sides of the equation are divided by the latent heat of vaporization, the product is the evapotranspiration, in grams per square meter per second.

The determination of the Bowen ratio in the field is made by measuring the temperature and vapor pressure at two heights above the soil surface. At the study border, two thin wire thermocouples were located at 1 and 2 meters from the soil surface to measure the temperature difference, and a chilled-mirror hygrometer with intakes at 1 and 2 meters from the soil surface was used to measure the vapor-density difference.

One set of BREB equipment was placed in the center of each study border (fig. 2). Sensors to measure wind speed and direction also were installed at each site to ensure that the proper fetch was maintained. Fetch is the extent upwind of the crop that is being measured. All parameters were measured every minute and averaged over a 20-minute interval. The latent heat-flux density was calculated for each 20-minute interval and was averaged to determine average daily heat-flux density. Figures 8 through 10 show examples of the measured net radiation, measured soil heat flux, calculated sensible heat flux, and calculated latent heat flux for a sunny day with a well-watered field, a cloudy day with a well-watered field, and a sunny day in a cut field.

One problem with the BREB method of measuring evapotranspiration occurs when the Bowen ratio nears the value of -1. In equation 9, as the denominator in the equation approaches zero, the solution becomes erratic. This phenomenon usually occurs with data collected at sunrise and sunset. To alleviate this problem, a micrometeorological method described by Arya (1988) was used to calculate evapotranspiration for each 20-minute interval when the Bowen ratio was between -0.6 and -1.4. This method requires wind speed at one height and air temperature at two heights to calculate *H*. *LE* is then calculated using equation 1. The *LE* values calculated during the intervals when the Bowen ratio approached -1 were very close to the values calculated before and after by the BREB method.

At several times during data collection, the vapor-pressure sensors in both sets of BREB instruments malfunctioned. Daily evapotranspiration during these time periods was estimated using the Priestley-Taylor method (Priestley and Taylor, 1972). This method uses net radiation, soil heat flux, psychrometric constant, slope of the saturation vapor pressure-temperature curve, and a factor called the Priestley-Taylor alpha. All data needed to determine daily evapotranspiration using this method were collected. The equation for this method is:

$$LE = \alpha . \frac{s}{s + \gamma} (R_n - G) \tag{10}$$

where α is Priestley-Taylor constant;

s is slope of the saturation vapor pressure-temperature curve; and

γ is psychrometric constant.

Priestley and Taylor (1972) developed an alpha of 1.26 for broad-scale estimations of evapotranspiration under saturated conditions and with minimal advection. The study sites were under saturated to semisaturated conditions for most of the time between irrigations, and evapotranspiration, based on soil moisture, was fairly constant. Prior to alfalfa starting to bloom and after alfalfa was cut, the soil moisture was depleted to the point that evapotranspiration declined. The study sites also had a large amount of advection due to wind coming off the nearby desert, which caused the alpha to increase. A new alpha of 1.51 was calculated by averaging

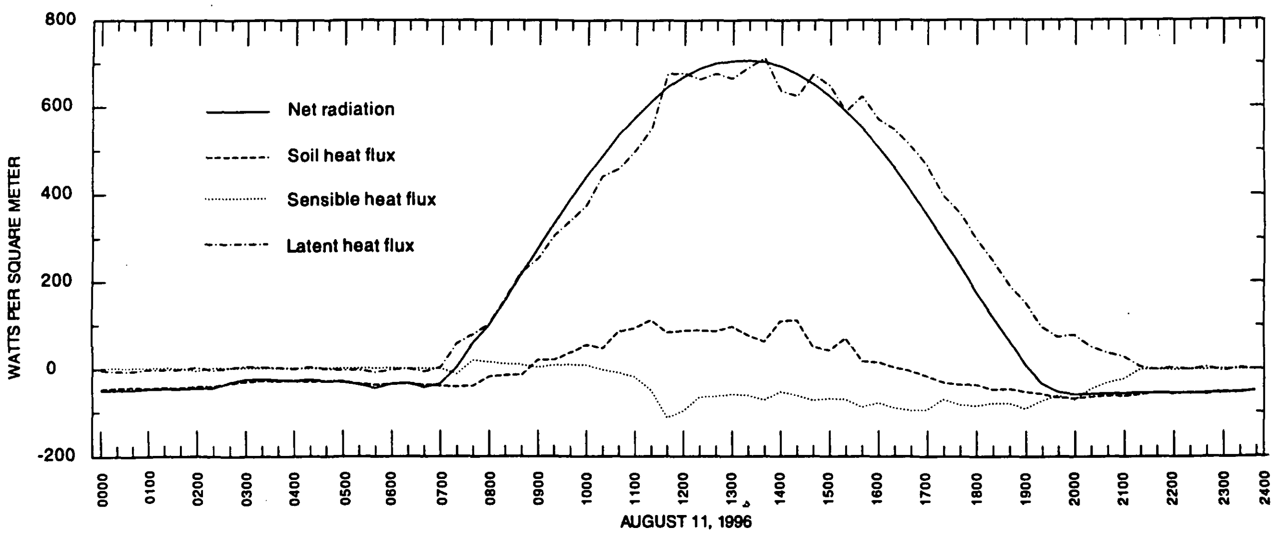

Figure 8.--Example of net radiation, soil heat flux, sensible heat flux, and latent heat flux during a sunny day in a well-watered border, Roswell Basin, New Mexico.

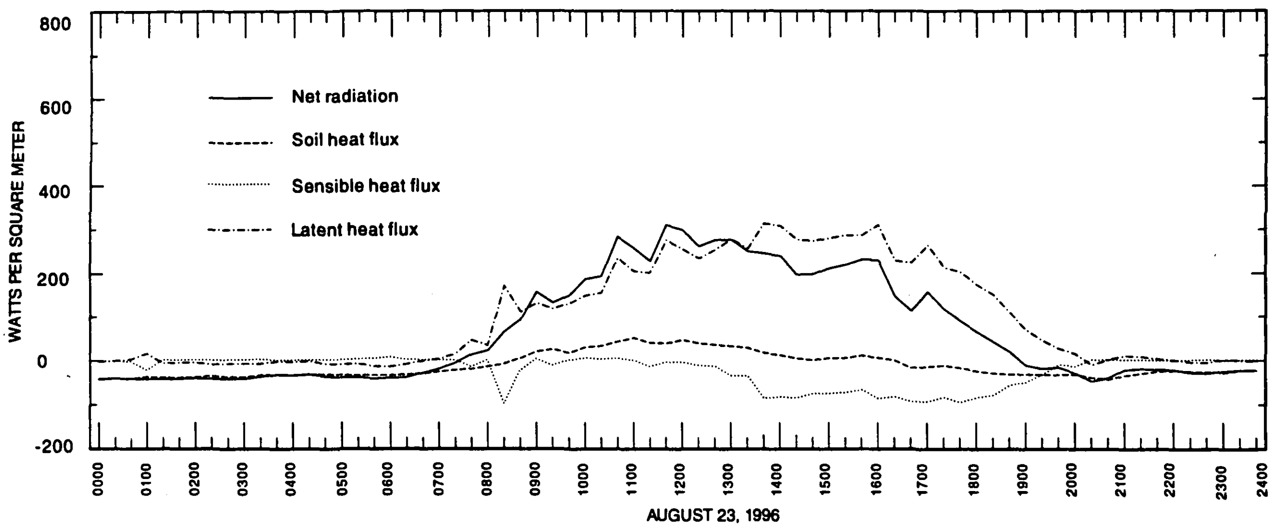

Figure 9.--Example of net radiation, soil heat flux, sensible heat flux, and latent heat flux during a cloudy day in a well-watered border, Roswell Basin, New Mexico.

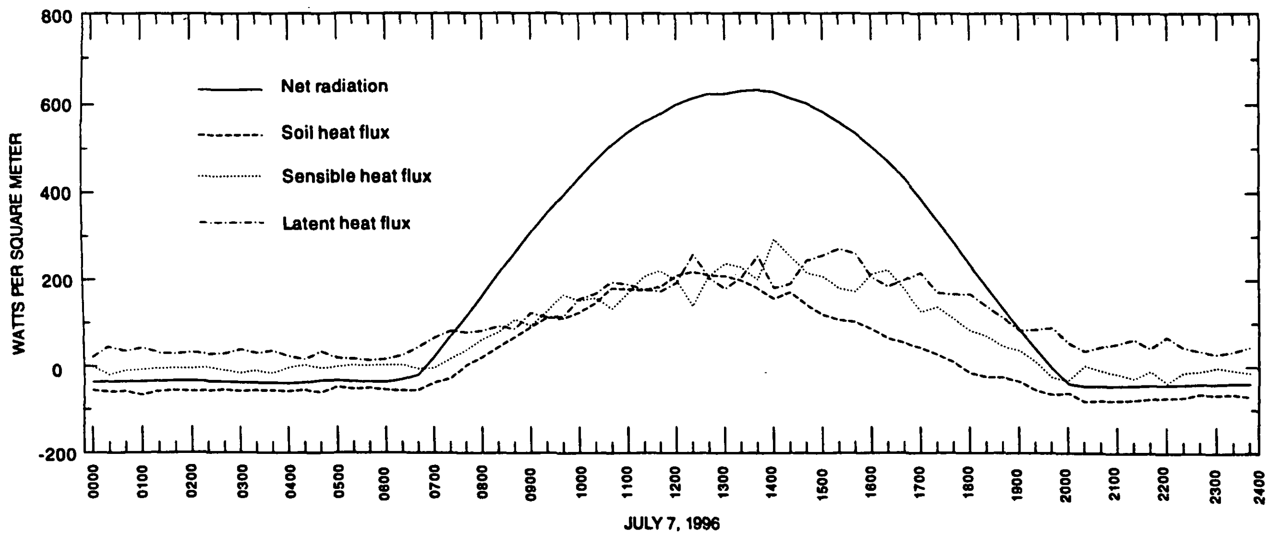

Figure 10.--Example of net radiation, soil heat flux, sensible heat flux, and latent heat flux during a sunny day in a cut border, Roswell Basin, New Mexico.

computed alphas from the Priestley-Taylor equation obtained during successful data collection. During these times all parameters in equation 10 except Priestly-Taylor alpha were available from the Bowen ratio data set. The standard deviation of the average alpha is 0.21. An alpha of 1.51 gave an accurate estimate of the latent heat flux when the latent heat flux was above 150 watts per square meter. Below this value the value of the alpha decreased sharply to 1.06. An alpha of 1.51 was used in the calculations when the latent heat flux was above 150 watts per meter, and a value of 1.06 was used when the latent heat flux was below 150 watts per meter.

Graphs of daily evapotranspiration in each study border are shown in figures 11 and 12. Most short-term decreases in evapotranspiration are due to cloud cover. The decreases in evapotranspiration for a prolonged period of time around May 30, July 2, August 6, August 26, and after September 16, 1996, are due to cutting of the alfalfa. The total estimated evapotranspiration for the irrigation season in the west study border was 97.8 centimeters and in the east study border was 101.0 centimeters.

Soil Moisture

Soil moisture was measured in five neutron-moisture-meter access holes, three (holes 1, 2, and 3) in the west study border and two (holes 1 and 3) in the east study border (fig. 2). The holes were cored for the entire 600-centimeter depth. A sample of the soil from the core was collected about every 61 centimeters. The sample was immediately sealed in an air-tight autoclavable container, and the volume of the sample was noted. The 2.5-centimeter core hole was hand augered with a 6-centimeter-diameter auger barrel to enlarge the hole, and 5.5-centimeter galvanized pipe was then screwed into the hole to assure a tight fit. A neutron-moisture meter was used to make neutron-count measurements every 61 centimeters to correlate with the soil samples. Four of the five access holes were completed to 600 centimeters; in access hole 3 in the east study border, however, the surrounding clay material moved back up into the pipe when the pipe was put in place, so that neutron-count measurements could be made only to 540 centimeters.

At the laboratory, the samples were weighed to determine their wet mass, then oven dried at 100 degrees Celsius until they lost no more water. The samples were weighed during the drying process until the mass did not change to ensure that all free water was lost. At that time, the samples were reweighed to determine their dry mass. Bulk density was determined for each soil sample by dividing the mass of the dry sample by its bulk volume. By using bulk density and the mass of soil and water, the volumetric-moisture content, θ, was determined for each sample with the following equation:

$$\theta = \left(\frac{\rho_b}{\rho_w}\right) \cdot \left(\frac{(m_w - m_d)}{(m_d - m_c)} \cdot 100\right) \tag{11}$$

where ρ_b is bulk density, in grams per cubic centimeter;

ρ_w is density of water, in grams per cubic centimeter;

m_w is wet sample mass, in grams;

m_d is dry sample mass, in grams; and

m_c is container mass, in grams.

The natural log of the volumetric soil-moisture content calculated for each of the samples was plotted against the neutron-moisture meter counts measured when the samples were collected to determine a calibration curve for the neutron-moisture meter (fig. 13). The calibration equation and the R squared value are also shown in figure 13.

Prior to each irrigation event, a soil-moisture profile was taken at 20-centimeter intervals at each neutron-moisture-meter access hole. Numerous soil-moisture profiles were then taken during and after the irrigation event to track the movement of irrigation water.

The movement of water in the soil around each access hole was determined by the length of time that the soil was submerged, the soil permeability at the surface, the amount of clay in the soil-moisture profile, and antecedent soil moisture. All soil-moisture profiles displayed similar trends during each irrigation event.

Near each access hole in the west study border, the main wetting front moved down the soil-moisture profile until it reached a clay layer, then a small amount of water continued to the bottom of the soil profile. As an example, near holes 1 and 2 in the west study border the soil moisture increased rapidly through the silt in the upper 220 to 260 centimeters of the soil profile; the wetting front then essentially stopped below the silts

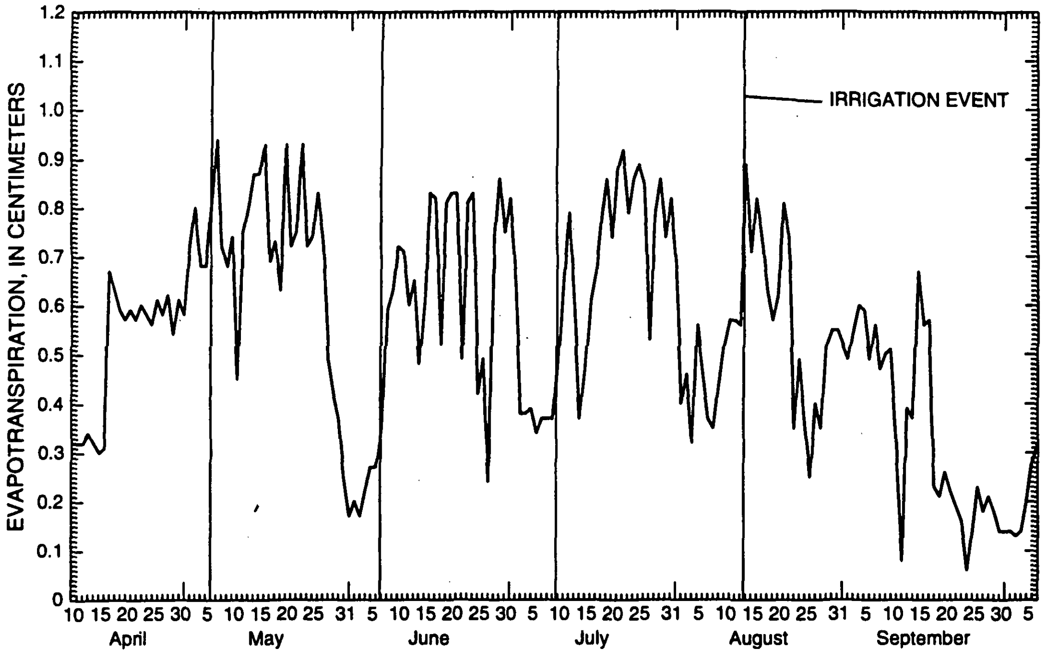

Figure 11.--Daily evapotranspiration in the west study border, Roswell Basin, New Mexico, 1996.

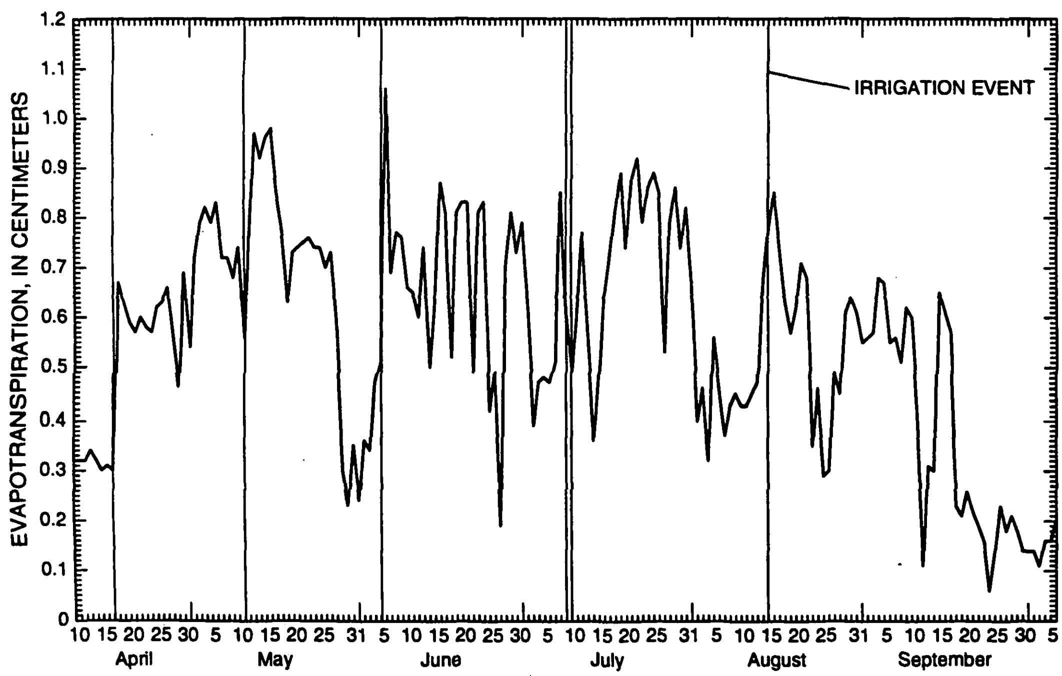

Figure 12.--Daily evapotranspiration in the east study border, Roswell Basin, New Mexico, 1996.

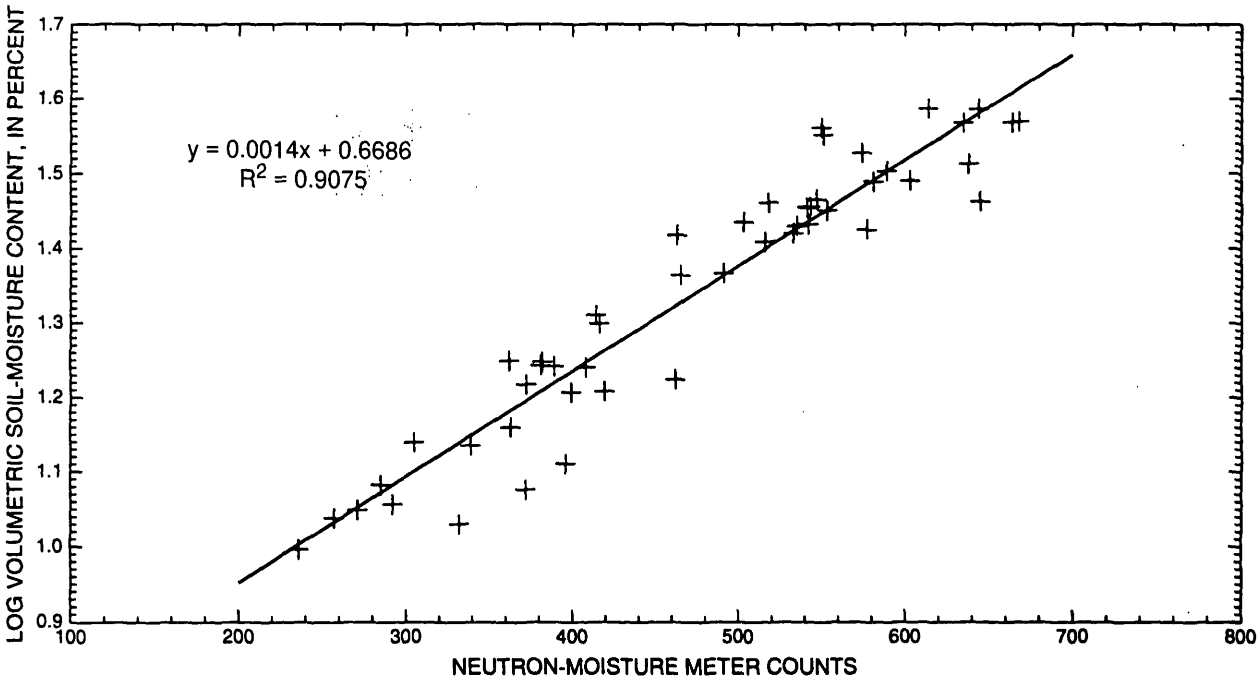

Figure 13.--Relation of volumetric soil-moisture content to neutron-moisture meter counts in study borders, Roswell Basin, New Mexico.

where clay was encountered (figs. 14 and 15). At greater depths, some movement of water can be seen. This increase possibly could be due to the presence of macropores in the clay that allow water to move through the clay without detection by the moisture meter. During all irrigation events, the soil-moisture profiles in west study border hole 3 (fig. 16) were submerged for the shortest period of time of any of the measured soil profiles, which limited the depth of the wetting front.

In east study border hole 1 (fig. 17), which contained less clay, the wetting front moved to greater than 300 centimeters, and more water moved completely through the 600-centimeter soil profile. The soil-moisture profiles in east study border hole 3 and west study border hole 3 (figs. 18, 19, and 16) had water on them for a shorter period of time than the rest of the access holes, but the wetting front in the east study border hole moved farther through the soil profile because of a larger percentage of sand.

The estimates of change in soil moisture were used in two of the three methods to estimate deep percolation. These estimates are directly related to the repeatability and accuracy of measurements made with the neutron-moisture meter. The repeatability and accuracy depend on many factors that are controlled by the environment in which the neutron-moisture meter is used. The relation between soil moisture and neutron-moisture meter counts shown in figure 13 is a good indication of high repeatability and accuracy of the meter. The standard deviation of the residuals of the regression transformed to percent volumetric-moisture content is 1.13. The measurements used in developing the relation shown in figure 13 were made over a 2-year period in all of the access holes.

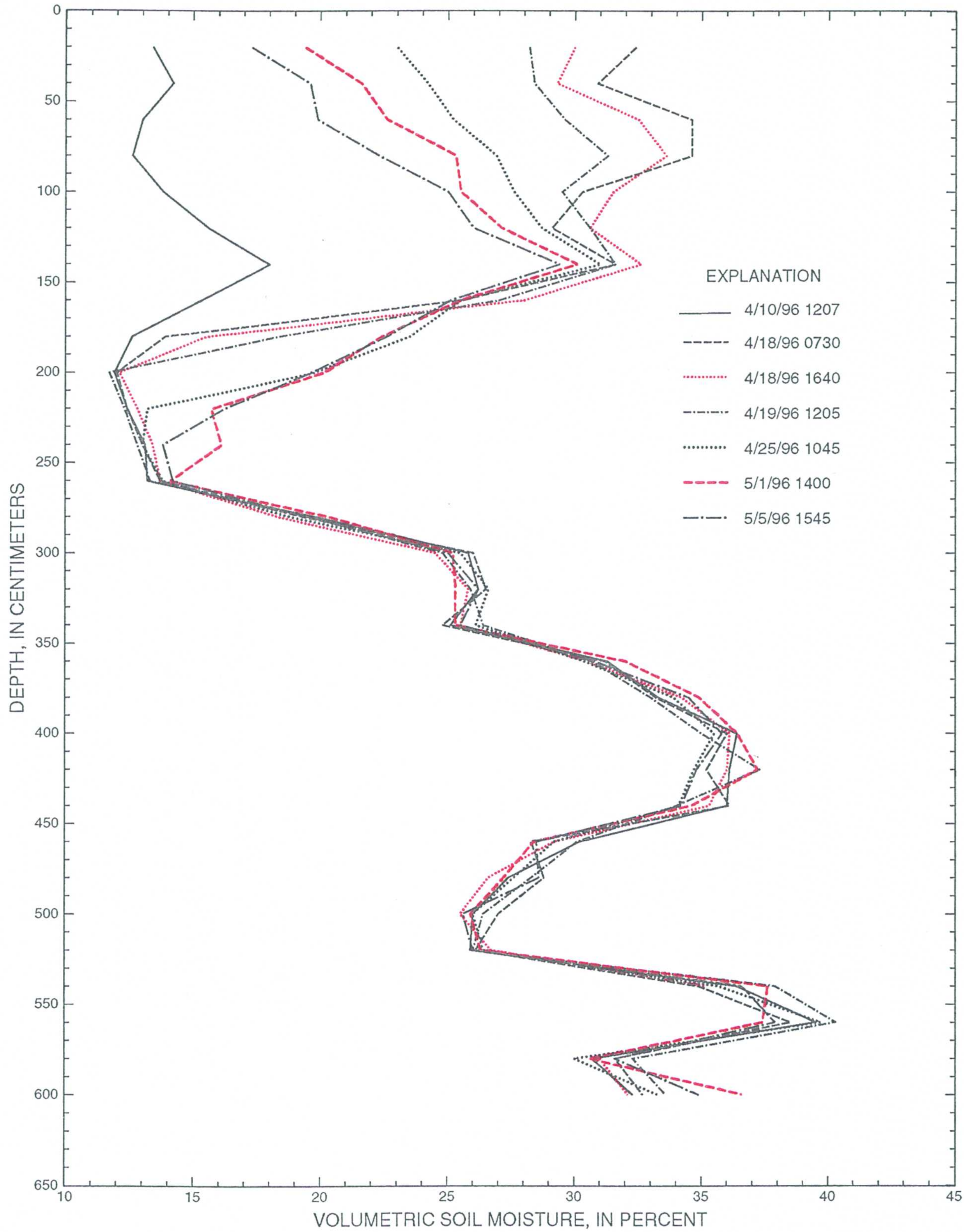

Figure 14.--Soil-moisture profiles for first irrigation event at west study border hole 1, Roswell Basin, New Mexico, 1996.

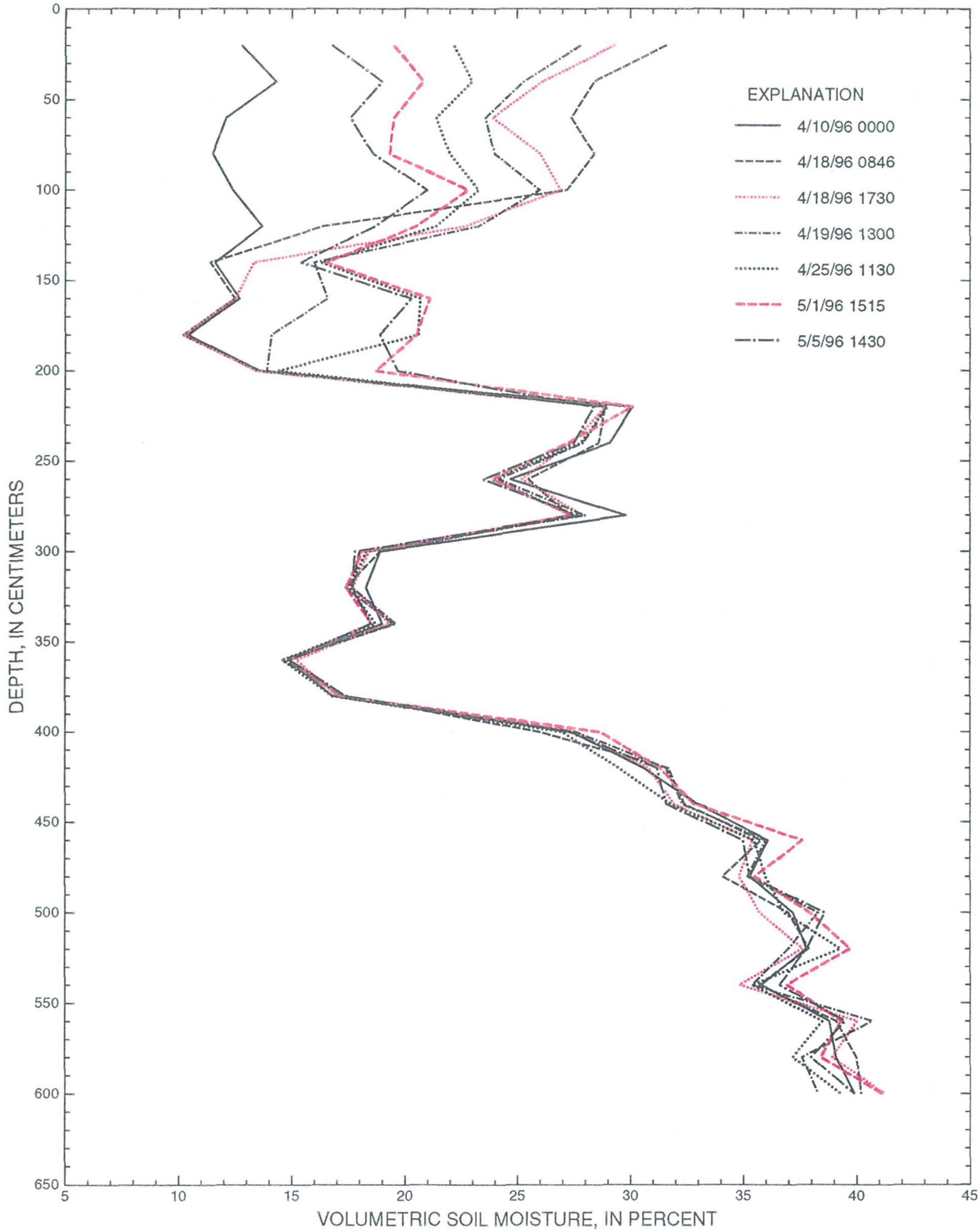

Figure 15.--Soil-moisture profiles for first irrigation event at west study border hole 2, Roswell Basin, New Mexico, 1996.

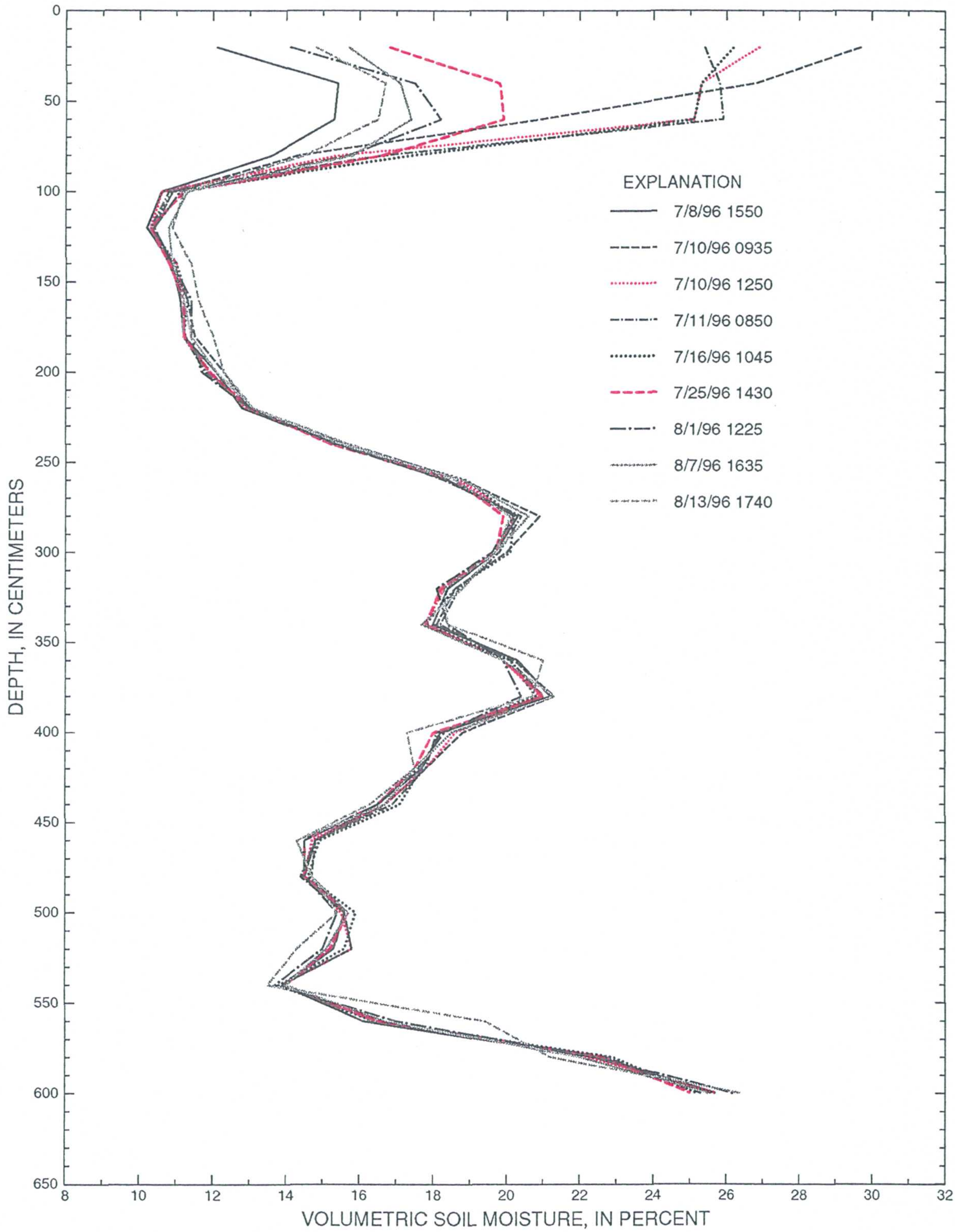

Figure 16.--Soil-moisture profiles for fourth irrigation event at west study border hole 3, Roswell Basin, New Mexico, 1996.

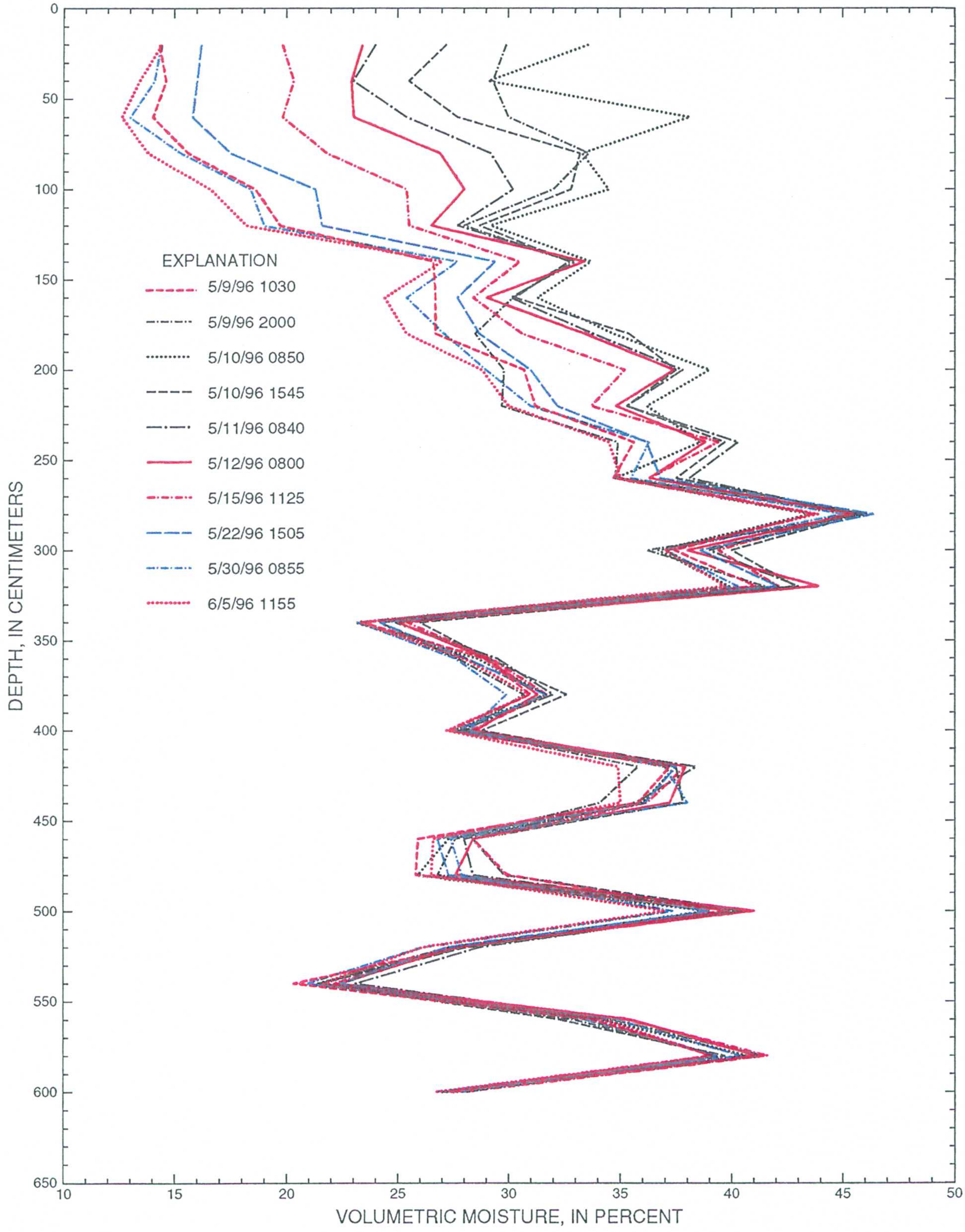

Figure 17.--Soil-moisture profiles for second irrigation event at east study border hole 1, Roswell Basin, New Mexico, 1996.

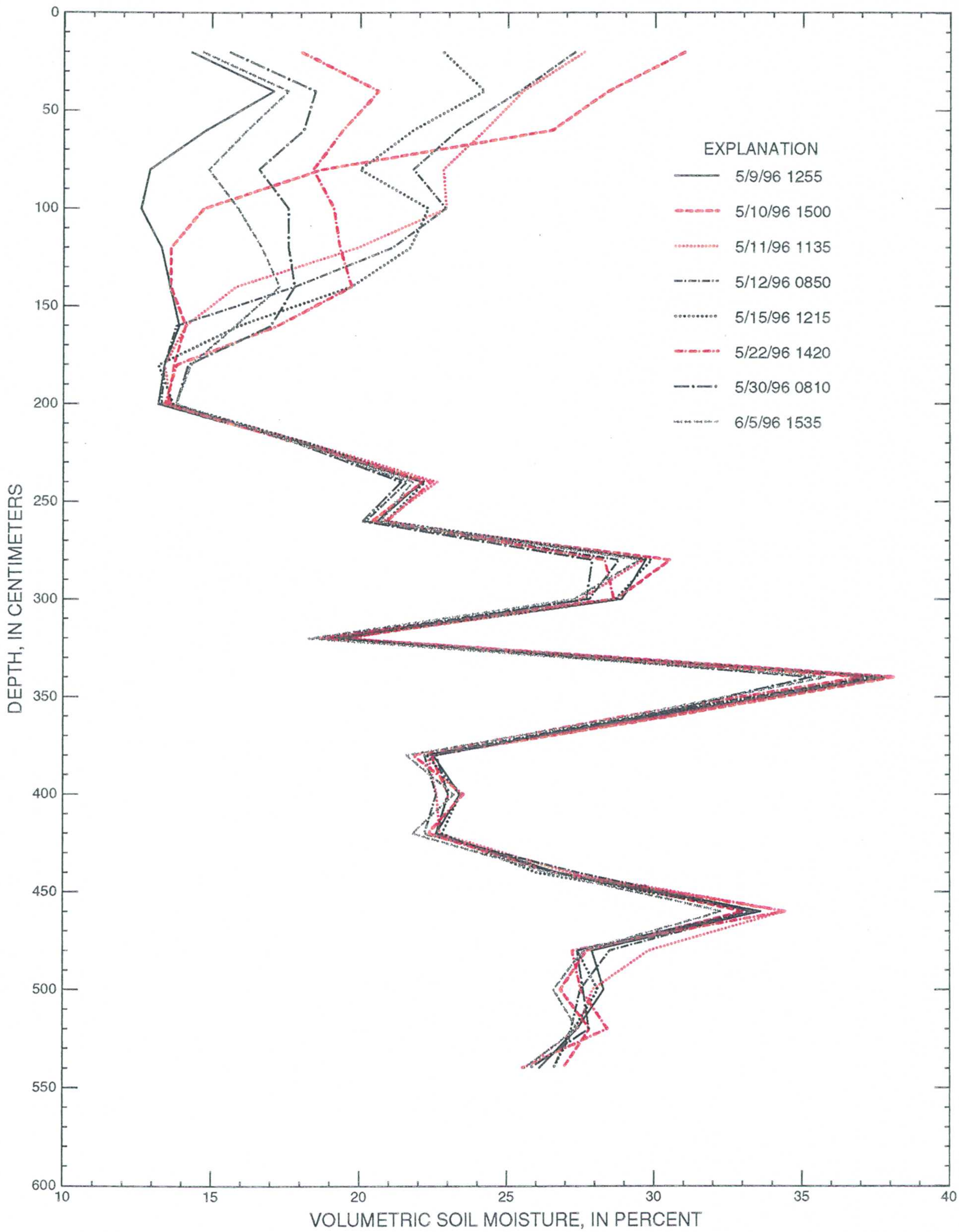

Figure 18.--Soil-moisture profiles for second irrigation event at east study border hole 3, Roswell Basin, New Mexico, 1996.

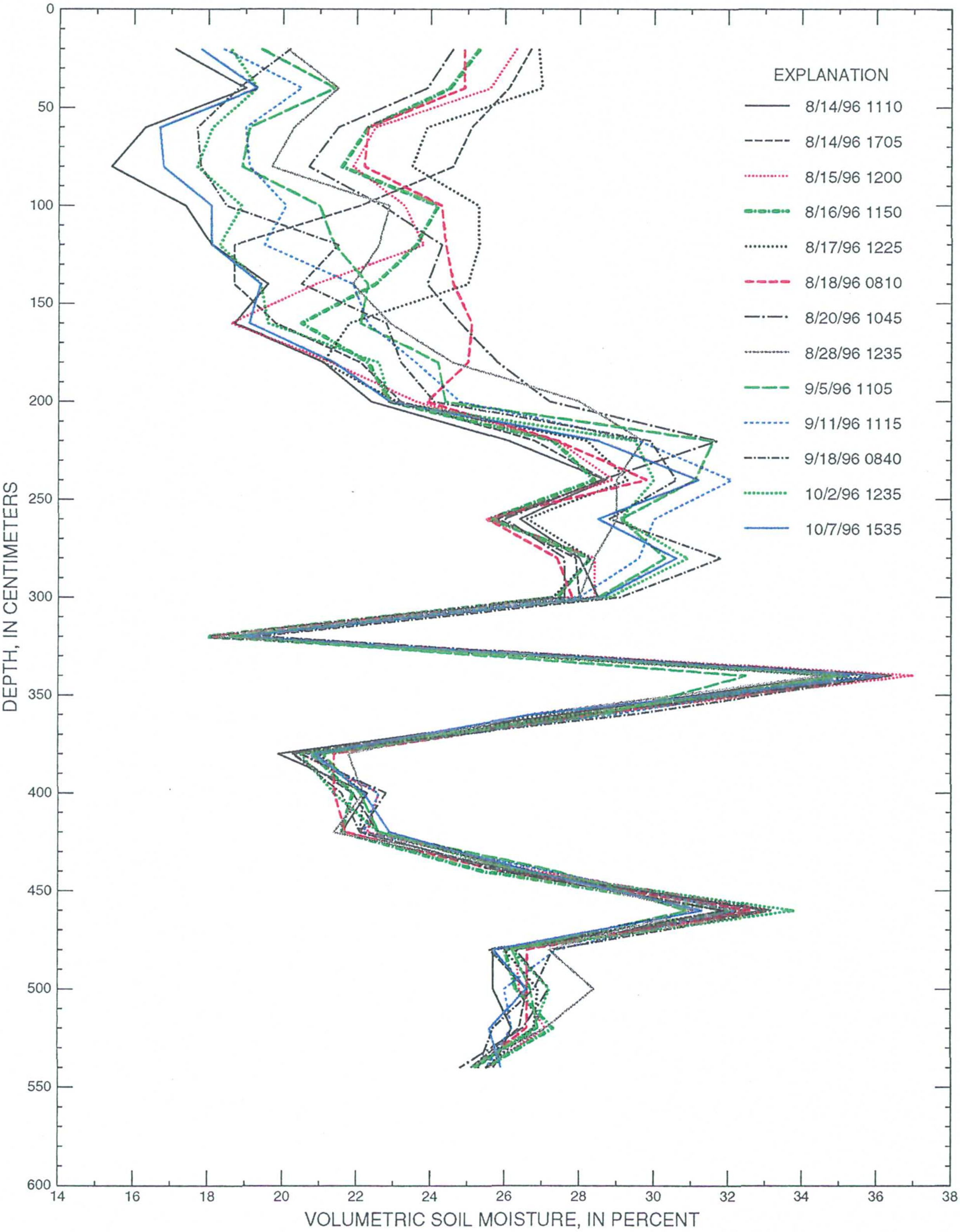

Figure 19.--Soil-moisture profiles for fifth irrigation event at east study border hole 3, Roswell Basin, New Mexico, 1996.

QUANTIFICATION OF DEEP PERCOLATION BY THE WATER-BUDGET METHOD

Method

The general equation for calculating a water budget in an irrigated field sums all possible parameters that add and subtract water from the surface of the field. The general equation is:

$$I + P - T - ET - \Delta S - B - D = 0 \qquad (12)$$

where I is irrigation water applied, in cubic centimeters per day;

P is precipitation, in cubic centimeters per day;

T is tail-water flow, in cubic centimeters per day;

ET is evapotranspiration, in cubic centimeters per day;

ΔS is change in soil moisture, in cubic centimeters per day;

B is water in crop biomass, in cubic centimeters per day; and

D is deep percolation, in cubic centimeters per day.

The water-budget calculations for the study borders in the Roswell Basin were simplified because some parameters were not significant. The water in the crop biomass that was cut and removed from the border was assumed to be so small compared with the rest of the water budget that it was not included in the calculations. The borders used in the study were irrigated in such a way that little or no water was removed from the border by tail-water runoff; therefore, this parameter also was not included in the calculations. Without these two parameters, deep percolation can be calculated as:

$$D = I + P - ET - \Delta S. \qquad (13)$$

The total amount of deep percolation for the irrigation season in each study border was calculated using daily evaporation estimates. Irrigation, precipitation, and change in soil moisture were included in the calculations on the day that they occurred or when measurements were taken. Changes in soil moisture from measurement to measurement were assumed to have been caused by moisture leaving the system by evapotranspiration or deep percolation. The change in soil moisture calculated for the west study border was the mean of the changes in soil moisture in the soil profiles at the top, middle, and bottom of the border. The change in soil moisture calculated for the east study border was the mean of the change in soil moisture in the soil profiles at the top and bottom of the border.

Results

Table 3 lists the irrigation season water-budget components for the two study borders. The borders had different results in the amount of deep percolation due to the amount of water that was applied. Soil moisture in the east study border changed more than that in the west study border; evapotranspiration also was slightly higher in the east study border due to the soil texture. The west border hole contained more silt and clay, which tend to hold more water and give up less water to plants, evaporation, and deep percolation. The retention of soil water depends directly on the pore size and pore-surface area, which depend directly on the soil texture (Hillel, 1982). The larger the pore size and the smaller the pore-surface area, as in sandy material, the greater the amount of water that will be released to plants, evaporation, and deep percolation. Of the total amount of water supplied to the border by applied irrigation water and precipitation, deep percolation accounted for 14 percent in the west study border and 43 percent in the east study border.

QUANTIFICATION OF DEEP PERCOLATION BY THE VOLUMETRIC-MOISTURE METHOD

Method

To determine the amount of deep percolation by the volumetric-moisture method, the total volume of water must be partitioned into water moving up and out of the soil profile by evapotranspiration or water moving down to become deep percolation. This can be accomplished using the zero flux plane. The zero flux plane is a plane at which the total head gradient in the vertical direction is zero. The assumption was made that any soil moisture below the zero flux plane will go to deep percolation and any moisture above it will go to evapotranspiration (Dreiss and Anderson, 1985, p. 505). When using this method, all moisture is assumed to move vertically. Although several soil-matric-potential sensors were installed in the study borders to monitor local head gradients, all failed soon after installation. Therefore, the depth of the zero flux plane was estimated from the plots of soil moisture. All plots of each soil-moisture profile were examined to determine the depth at which the effects of the root and surface zone could not be seen. The zero flux plane is not at a fixed depth over time; it moves up near the surface for short periods of time when the border is irrigated and moves deeper as the border dries out near the surface. The constant depth that was chosen for the calculations approximates the depth at which the zero flux plane will be at for the longest period of time.

The amount of water passing through the bottom of all soil layers below the zero flux plane was calculated by using the following technique. The amount of water in each layer during a measurement was summed over the thickness from the zero flux plane to the bottom of the hole, assuming a unit diameter and 20-centimeter layer thickness. The amount of soil water calculated was subtracted from the soil water calculated from the previous measurement. All positive changes were caused by water entering the soil column, and all negative changes were caused by water leaving the column. If water is entering the soil column, the zero flux plane will move upward to near the surface during irrigation and then back down to below the root zone as the field dries out near the surface. Using the method of estimating depth of the fixed zero flux plane, the zero flux plane is assumed to move upward over an extremely short amount of time compared with the time that it is near the estimated depth. All negative changes in soil-moisture content were summed to give the total amount of water leaving the bottom of the soil profile due to deep percolation.

Results

Table 4 shows the estimated depth of the zero flux plane and the amount of deep percolation calculated for each soil-moisture profile. The average deep percolation for the three west study border soil profiles was 22.3 centimeters and for the two east study border soil profiles was 31.6 centimeters. The deep percolation calculated by the volumetric-moisture method for the west study border accounted for 19 percent and for the east study border accounted for 16 percent of the total amount of water supplied to the border by applied irrigation water and precipitation. The average for the east study border holes could be smaller than the actual average for the border because no volumetric-moisture data were obtained for the center of the border as was done for the west study border.

A decrease in the amount of deep percolation was observed for the bottom of both study borders due to the method of irrigation used. In most cases, the siphon tubes were moved to another border before water had ponded at the bottom of the field.

QUANTIFICATION OF DEEP PERCOLATION BY THE CHLORIDE MASS-BALANCE METHOD

Method

Deep percolation rates were calculated by a mass-balance method that uses chloride as a natural tracer (Stone, 1991). This method assumes no source of chloride in the soil, steady-state chloride concentrations in the input water, and piston flow in the unsaturated zone. Under these conditions, chloride concentration should increase in the root zone when water is lost to transpiration. A typical plot of chloride concentration and depth shows chloride concentration peaking in the root zone (Stone, 1991). Below this peak, the chloride concentration should be constant (Allison and others, 1985).

This method used cores collected during the installation of neutron-moisture-meter access holes and other soil-moisture equipment in the center of each border for which soil moisture and bulk density were calculated. A known quantity of inorganic blank water was added to each dried core section, and the mixtures were shaken for 7 hours. A chloride ion-selective probe was calibrated with chloride-concentration standards and used to measure the chloride concentration in the extracts (fig. 20) (McGurk and Stone, 1985). Chloride

Table 3.--Calculated irrigation season water-budget components for study borders, Roswell Basin, New Mexico

Water-budget component	West study border depth of water (centimeters)	East study border depth of water (centimeters)
Applied irrigation water	95.8	169.8
Precipitation	21.9	21.9
Soil-moisture change	3.2	8.8
Evapotranspiration	98.1	101.3
Deep percolation	16.4	81.6

Table 4.--Determined zero flux planes and calculated deep percolation using volumetric-moisture method, Roswell Basin, New Mexico

Soil profile	Depth of zero flux plane (centimeters)	Deep percolation (centimeters)
West study border hole 1	300	27.7
West study border hole 2	320	24.4
West study border hole 3	280	14.7
East study border hole 1	320	38.2
East study border hole 3	280	25.1

concentrations in the core water were calculated by the equation (modified from Stone, 1991):

$$Cl_{cw} = \left(\frac{(Cl_e \cdot H_2O_a)}{(m_d \cdot \theta)} \right) \cdot \rho_b \qquad (14)$$

where Cl_{cw} is chloride concentration of core water, in milligrams per liter;

Cl_e is chloride concentration of extract, in milligrams per liter;

H_2O_a is weight of inorganic blank water added, in grams;

m_d is dry weight of core section, in grams;

θ is moisture content of core section; and

ρ_b is bulk density of core section.

Table 5 lists the moisture content, dry weight, bulk density, chloride concentration in the extract, and chloride concentration in the core water for each core section.

The chloride core-water concentrations were plotted against depth (fig. 21). For the west study border core, a chloride peak was observed at 176 centimeters. Below this peak, chloride core-water concentrations averaged 174 milligrams per liter. For the east study border core, chloride core-water concentrations reached a peak at 359 centimeters and averaged 126 milligrams per liter below 420 centimeters. Deep percolation was calculated by the equation:

$$D = \left(\frac{(P \cdot Cl_P) + (I \cdot Cl_I)}{Cl_{sw}} \right) \qquad (15)$$

where D is deep percolation rate, in meters per year;

P is average precipitation, in meters per year;

Cl_p is average chloride concentration in precipitation, in milligrams per liter;

I is average amount of applied irrigation water, in meters per year;

Cl_I is average chloride concentration in irrigation water, in milligrams per liter; and

Cl_{sw} is average chloride concentration in core water below the chloride peak, in milligrams per liter.

An average precipitation rate of 34.4 centimeters per year for 1973-96, obtained from the National Weather Service rain gage at the Roswell Industrial Air Park, was used in the calculations. An average chloride concentration in precipitation of 0.087 milligram per liter for 1984-95 was obtained from the National Atmospheric Deposition Program monitoring station at Mayhill, New Mexico, approximately 110 kilometers west-southwest of the study borders (National Atmospheric Deposition Program, 1997). The 1996 irrigation season application of 95.8 centimeters to the west study border and 169.8 centimeters to the east study border (table 3) was used for the average irrigation rate. An average chloride concentration of 28 milligrams per liter for 1988 to 1997 was obtained from three samples from the irrigation-supply well.

Results

The calculated deep percolation rate for the west study border was 15.0 centimeters per year and for the east study border was 38.0 centimeters per year. The deep percolation calculated by the chloride mass-balance method in the west study border accounted for 13 percent and in the east study border accounted for 20 percent of the total amount of water supplied to the border by applied irrigation water and precipitation. The amount of applied irrigation water can vary considerably from year to year, depending on precipitation, temperature, and crop type. The cores that were used for chloride analysis were collected to the greatest depth that could be achieved with the equipment available, but the cores were too short for a conclusive analysis of average soil water concentration. The chloride concentration used for soil water should be averaged over 30.5 meters or the entire vadose zone, whichever is shorter (Stone, 1991).

An examination of the above data shows that the precipitation contributions to chloride concentrations in soil water for this study area are negligible, approximately 0.1 percent or less, compared to the irrigation water contribution. If the precipitation contribution were ignored, the calculated deep percolation rates would not change significantly.

The chloride concentrations of 10, 28, and 46 milligrams per liter in three samples from the irrigation-supply well showed a high degree of variation: the mean concentration was 28 milligrams per liter and the standard deviation was 18 milligrams per liter. This contradicts the basic assumption of

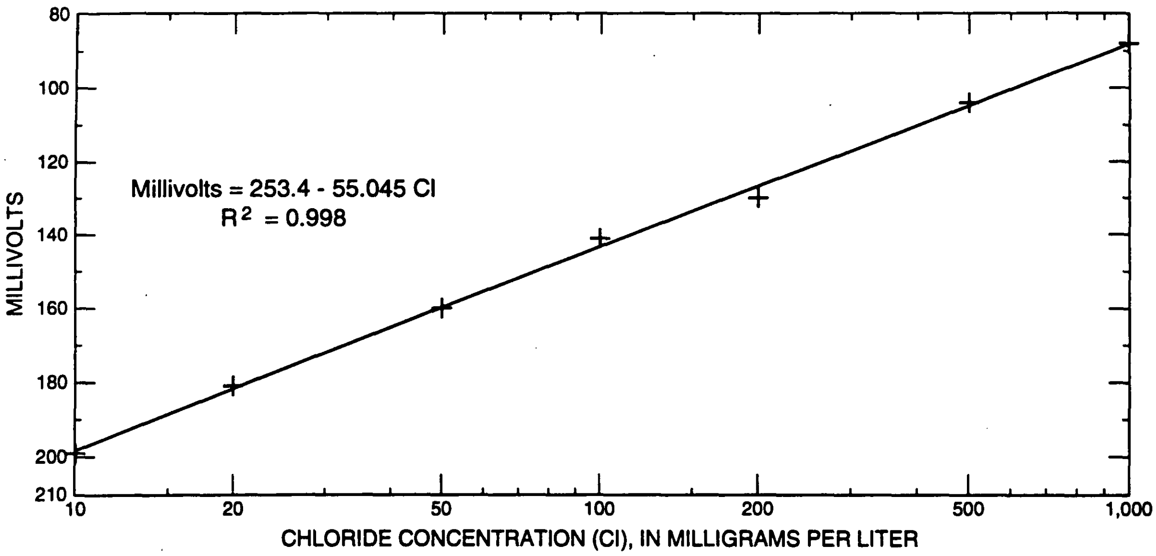

Figure 20.--Chloride standardization curve for millivolt readings, Roswell Basin, New Mexico.

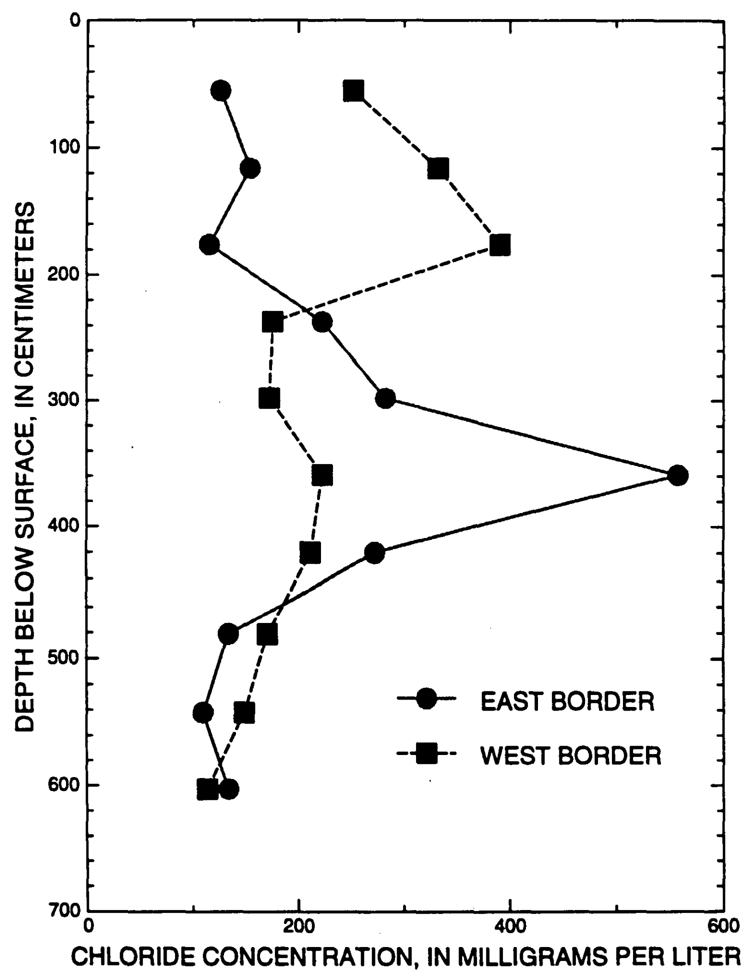

Figure 21.--Chloride concentrations in core water, Roswell Basin, New Mexico.

Table 5.--Chloride concentrations in selected core samples, Roswell Basin, New Mexico

[mg/L, milligrams per liter]

Depth below land surface (centimeters)	Moisture content (percent)	Dry weight (grams)	Water-added weight (grams)	Bulk density (unitless)	Chloride concentration in extract (mg/L)	Chloride concentration in core water (mg/L)
West study border hole 2						
55	12.7	62.862	68.828	1.082	27	252
116	11.4	69.265	62.752	1.192	35	332
176	10.2	68.975	68.202	1.187	34	391
237	22.9	67.981	68.750	1.170	34	176
298	13.4	75.339	61.299	1.296	22	173
359	8.4	82.367	49.475	1.417	22	223
420	22.0	81.161	79.692	1.396	34	212
481	26.9	83.273	86.439	1.433	31	171
542	22.3	75.636	74.458	1.301	26	149
603	27.2	78.931	90.318	1.358	20	114
East study border hole 2						
55	12.6	60.297	71.608	1.333	10	126
116	13.0	55.451	64.693	1.226	14	154
176	23.8	61.416	94.441	1.057	17	116
237	11.1	83.309	74.717	1.841	15	223
298	22.8	94.775	81.121	1.631	46	283
359	14.1	105.804	71.241	2.338	50	558
420	27.6	60.16	66.816	1.330	51	273
481	22.4	71.652	61.715	1.584	22	134
542	28.4	68.185	64.297	1.507	22	110
603	15.8	93.478	63.982	2.066	15	134

steady-state chloride input. The 28-milligram-per-liter concentration used in the deep percolation calculations gives an approximate median deep percolation rate for the two study borders. If the minimum and maximum measured chloride concentrations were used to calculate deep percolation, the deep percolation rate for the west study border would range from 5.5 to 25.3 centimeters per year and for the east study border would range from 13.5 to 62.0 centimeters per year.

COMPARISON OF DEEP PERCOLATION ESTIMATES, POSSIBLE ERRORS, AND RELATION OF THIS STUDY TO THE ROSWELL BASIN

The range of estimates of deep percolation in the west study border is smaller than that in the east study border. The estimates for the west study border are in good agreement: the water-budget method gives a value of 16.4 centimeters, the volumetric-moisture method gives an average of 22.3 centimeters, and the chloride mass-balance method gives a value of 15.0 centimeters of water. The estimates for the east study border have a wider range: the water-budget method gives a value of 81.6 centimeters, the volumetric-moisture method gives an average of 31.6 centimeters, and the chloride mass-balance method gives a value of 38.0 centimeters of water.

The amount of deep percolation in the west study border appears to be limited by surface permeability and soil profile texture. The crops in fields in the Roswell Basin are rotated between alfalfa, cotton, and wheat. Each crop type has a different type of irrigation that uses a different amount of water. Therefore, if crop or type of irrigation is the determining factor, the estimates derived from the water-budget and the volumetric-moisture methods would be different than those derived from the chloride mass-balance method.

The variability in the estimates of deep percolation in the east study border could be caused by several factors. The speed at which water moves through the soil profile would affect results derived from the volumetric-moisture method because this method relies on measurements of soil-moisture changes only. Measurements of soil moisture were made two or three times on the day of irrigation, and once a day for a week after that. The frequency of measurements on the day of irrigation was based on the time required to measure all five access holes, about 5 hours. If some of the water was moving rapidly through macropores, the number of measurements would not be sufficient to detect all water moving out of the soil profile and the amount of deep percolation would be underestimated. The number of measurements would not affect results derived from the water-budget method because any water missed in the measurement of soil moisture would by default be calculated as deep percolation.

Another cause of errors using the volumetric-moisture method is the uncertainty on the exact location of the zero flux plane in each of the soil-moisture profiles. The calculations of this method use the change in soil moisture below the zero flux plane. If the estimate of the location of the zero flux plane is too deep, the estimates of the amount of deep percolation can be too small. Because the method uses changes in soil moisture, the method also can yield low estimates of deep percolation if there is a great amount of steady-state flux rather than piston flow.

The amount of deep percolation determined by the water-budget method probably is the best estimate of deep percolation for 1996. The values calculated from the chloride mass-balance method, however, sum many years and many different crop types and, therefore, may be a better indicator of long-term, deep percolation.

The results of the water-budget method for the west study border should be applicable to most of the Roswell Basin that have fields flood irrigated with siphons, have similar field layout, and grow alfalfa. Because of the large amount of water applied to the east study border, the results of the water-budget method are biased toward greater amounts of deep percolation. If applied to the whole basin, these results could be misleading. As can be seen in table 3, the different components of the water budget did not vary greatly between study borders. The major difference in the estimates of deep percolation results from the amount of water applied to the border. Because the components of evapotranspiration, soil-moisture change, and precipitation did not vary significantly between the two study borders, deep percolation in the Roswell Basin can be modeled using the deep percolation model of Bauer and Vaccaro (1987) if the amount of applied irrigation water and the distribution of crops in the basin are known.

To obtain a better estimate of the amount of deep percolation from other sources in the Roswell Basin, further studies need to be undertaken. One possible source of continuous deep percolation in the basin is seepage from irrigation water storage ponds. These ponds hold water during the entire irrigation season and receive ground water that flows from the irrigation wells during the winter. The valves on the irrigation wells completed in the San Andreas aquifer are left cracked open to keep the wells from freezing during the winter, which allows a continuous flow of water into the ponds with little or no evaporation. A water-balance analysis of the ponds would provide an estimate of the amount of deep percolation. Another possible source of large amounts of deep percolation is from irrigation of newly planted row crops such as cotton. Fields are watered several times before the crop matures enough to transpire.

SUMMARY

For many years, water management in the Roswell Basin and other declared basins in New Mexico has been the responsibility of the State of New Mexico. One of the water management issues requiring better quantification is the amount of deep percolation from applied irrigation water so that the Office of the State Engineer and others can better understand the ground-water systems and estimate the amount of ground-water depletion in each basin. To address this issue, the U.S. Geological Survey in cooperation with the Office of the State Engineer studied a subplot or border in two adjacent fields in the Dexter area of the Roswell Basin in southeastern New Mexico to estimate the amount of deep percolation from flood irrigation.

Both study borders were planted with common alfalfa, the west study border during 1993 and the east study border during 1994. Soils in the two study borders are Reakor series soils, which are deep, well-drained soils. Particle-size distribution was determined at intervals in two sets of cores from neutron-moisture-meter access holes in each study border. Analysis of the cores from both borders shows that the soils are heterogeneous and contain significant layering. The particle sizes in the west study border cores are predominantly silt above 300 centimeters and clay below. The east study border cores contain a fairly even distribution of sand, silt, and clay except between 200 and 300 centimeters where silt is predominant.

Water for the study borders is pumped from a well completed in the San Andreas aquifer into a storage pond. Water is siphoned onto the borders for the period of time needed to cover each entire border. The amount of irrigation water applied to the study borders was measured during each irrigation event. The average time of application of water to the borders ranged from 2.0 to 8.5 hours at the west study border and from 2.9 to 13.5 hours at the east study border. The wide range in time that was needed to irrigate the borders was due to two main variables: permeability at the soil surface and the amount of time left in the day to water. Permeability is related to the amount of clay at the surface and the antecedent moisture at the surface. The timing and amount of precipitation that fell in the area of the study borders were recorded using a tipping-bucket rain gage and digital recorder. The total amount of precipitation that fell during the irrigation season was 21.9 centimeters.

Evapotranspiration was estimated using the Bowen ratio energy balance method; an alternative micrometeorological method was used when the Bowen ratio was between -0.6 and -1.4. When the vapor-pressure sensor failed on the Bowen ratio equipment, daily evapotranspiration was estimated using the Priestley-Taylor method. A new alpha of 1.51 was determined by averaging alphas computed using the Priestley-Taylor equation and the latent heat-flux density, air temperature, net radiation, and soil heat flux from the Bowen ratio data set. The total estimated evapotranspiration at the west study border was 97.8 centimeters and at the east study border was 101.0 centimeters for the irrigation season.

Soil moisture was measured in five neutron-moisture-meter access holes. Prior to each irrigation event, a soil-moisture profile was taken at 20-centimeter intervals at each neutron access hole. Numerous soil-moisture profiles were then taken during and after the irrigation event to track the movement of irrigation water.

Irrigation season deep percolation was 16.4 centimeters in the west study border and 81.6 centimeters in the east study border as calculated by computing daily cumulative deep percolation as part of the water-budget method. From the volumetric-moisture method, the average deep percolation in the three west study border soil profiles was 22.3 centimeters and in the two east study border soil profiles was 31.6 centimeters. From the chloride mass-balance method, the calculated deep percolation rate in

the west study border was 15.0 centimeters per year and in the east study border was 38.0 centimeters per year. The amount of deep percolation determined by the water-budget method probably is the best estimate of deep percolation for 1996. Of the total amount of water applied to the borders by applied irrigation water and precipitation, deep percolation accounted for 14 percent in the west study border and 43 percent in the east study border using the water-budget method.

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