Direct Determination of Crop Evapotranspiration in the Arkansas Valley With a Weighing Lysimeter

Abdel Berrada

January 2011

Completion Report No. 220

Colorado Water Institute

Colorado State University

Acknowledgements

This project funded by the Colorado Water Institute in the amount of $50,000, and matched dollar for dollar by Colorado State University, has resulted in establishing the baseline characteristics, capacity, and performance of the large lysimeter, its site, and the processes used to establish an initial alfalfa crop and to calibrate instrumentation for the conduct of subsequent work over two to three years to achieve objective 1 above (not funded herein). (See also Future Plans below.)

Project Participants:
Colorado Division of Water Resources
Colorado State University
Colorado Water Conservation Board
Colorado Water Institute
United States Department of Agriculture – Agricultural Research Service

This report was financed in part by the U.S. Department of the Interior, Geological Survey, through the Colorado Water Institute. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Additional copies of this report can be obtained from the Colorado Water Institute, E102 Engineering Building, Colorado State University, Fort Collins, CO 80523-1033 970-491-6308 or email: cwi@colostate.edu, or downloaded as a PDF file from http://www.cwi.colostate.edu.

Colorado State University

Direct Determination of Crop Evapotranspiration in the Arkansas Valley With a Weighing Lysimeter

Investigators and Contributors:
Lee E. Sommers
and Frank P. Johnson
Colorado Agricultural Experiment Station

Alan A. Andales
and Abdelfettah Berrada
Department of Soil and Crop Sciences

Michael E. Bartolo
Department of Horticulture and Landscape Architecture

Thomas W. Ley
and Dale Straw
Colorado Division of Water Resources

Bret Schafer
and Lane H. Simmons
Colorado State University Arkansas Valley Research Center

Reagan M. Waskom
Colorado Water Institute

Project 5-30205 Completion Report
Submitted to: Colorado Water Institute
August 21, 2009

Abstract:
The state of Kansas initiated litigation related to the state of Colorado's compliance with the Arkansas River Compact in 1985. Kansas asserted that post-Compact well development in Colorado was causing depletion of usable flows at the Colorado-Kansas state line (state line), and therefore, Colorado was in violation of the compact. A number of hydrological modeling issues were contested between the two states over the course of the litigation. Among these was the methodology for estimating potential crop consumptive use, an important input parameter to the Hydrological-Institutional (HI) Model. The HI Model was developed to determine depletions to usable Arkansas River streamflows at the state line caused by post-Compact well pumping in Colorado and to evaluate whether the state of Colorado is in compliance with the Arkansas River Compact between the two states. The modified Blaney-Criddle equation had historically been used for estimating crop consumptive use. Based on expert testimony regarding the inaccuracy of the Blaney-Criddle method and on the increasing availability of electronic weather station data in the area, the special master (appointed to carry out duties on behalf of the court) recommended that crop consumptive use estimates for input to the HI Model should be based on a reference crop evapotranspiration (ET) mean crop coefficient approach. Specifically, the American Society of Civil Engineers (ASCE) Standardized Reference ET Equation (ASCE-EWRI, 2005) and available electronic weather station data should be used to estimate tall (alfalfa) reference crop ET_{rs}, and alfalfa reference based mean crop coefficients adapted for the major crops grown in the area should be used to compute crop ET. Littleworth (the special master) did recognize: "…as more information is developed on conditions in the Arkansas River Valley, adjustments made in accordance with recognized professional procedures may be appropriate" (2003).

Colorado's response to the special master's decision was three-fold:

1. Construct and install two precision weighing lysimeters at Colorado State University's (CSU) Arkansas Valley Research Center to establish the infrastructure, including instrumentation, necessary to collect and validate the accuracy of crop water use under local conditions.
2. Initiate and conduct long-term studies to:
    - evaluate the performance and predictive accuracy of the ASCE Standardized Reference ET Equation for computing alfalfa reference crop ET for the growing conditions in southeastern Colorado;
    - determine crop coefficients (for use with the standardized equation) for the various crops grown in the Arkansas River Valley under well-watered conditions;
    - determine the effects of local growing conditions (limited irrigation, high water tables, and high soil/water salinity content) on crop water use.
3. Improve/enhance the Colorado Agricultural Meteorological Network (CoAgMet) electronic weather station network in the lower Arkansas Valley between Pueblo and the state line to provide the weather data necessary for the Standardized Equation.

The Colorado Water Conservation Board (CWCB) provided funding to CSU for the construction and installation of two precision weighing lysimeters: the large and reference lysimeters. The large lysimeter installation was completed in the spring of 2007 and the reference lysimeter was completed in the spring of 2009. This report focuses on accomplishments relative to the first objective in the above list, and specifically on details of the construction, calibration, and first operation of the large lysimeter. The following describes the processes and results in establishing the baseline characteristics, capability, and performance of the large lysimeter

Keywords: precision weighing lysimeter, evapotranspiration, Arkansas River Compact, ASCE, crop consumptive use

Table of Contents

List of Tables in Content Text

List of Figures in Content Text

List of Tables in Appendix A

1. Estimating Crop Evapotranspiration

The ASCE standardized reference evapotranspiration equation, ASCE std. Ref-ET Eq., (ASCE-EWRI, 2005) is based on the Penman-Monteith equation (Jensen et al., 1990) with standardized methodology for computing input parameters and coefficients used in the equation. The ASCE std. Ref-ET Eq. can be used to compute the evapotranspiration (ET_{sz}) of two hypothetical reference surface conditions – a short crop similar to clipped grass (ET_{os}), and a tall crop similar to full-cover alfalfa (ET_{rs}). Similar to most western U.S. States, Colorado uses alfalfa as reference crop. Meteorological data required for input to the equation are maximum and minimum air temperature (C), relative humidity (which in combination with air temperature is used to compute actual vapor pressure of the air (kPa)), incoming total shortwave solar radiation (MJ m^{-2} d^{-1}), and wind speed (m s^{-1}) measured at 2 m above the ground surface. Crop evapotranspiration (ET_c) is derived from reference ET (ET_{rs}) with the equation:

$$ET_c = K_c \times ET_{rs}$$

ET_{rs} is defined as the evapotranspiration of a non-stressed, well-watered hypothetical green crop surface with roughness characteristics similar to alfalfa, 50 cm in height, and fully covering the ground. K_c is a crop coefficient that varies with crop type, growth stage, and crop condition (plant density, health, etc.) for well-watered conditions.

When the crop is water-stressed:

$$ET_c = K_s \times K_c \times ET_{rs}$$

where the water-stress coefficient, K_s can be calculated with the equation:

$$K_s = (TAW - D_r) / [(1-p)\ TAW]$$

where D_r is the root zone water depletion (mm), TAW is the total available water in the root zone (mm), and p is the “fraction of TAW that a crop can extract from the root zone without suffering water stress” (Allen et al., 1998). Methods and examples of calculating K_c, K_s, and crop ET are given in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998).

Crop ET (ET_c) may be estimated using water balance methods:

$$ET_c = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW$$

where I is irrigation depth, P is precipitation (water from rain or snow), RO is runoff, DP is deep percolation, CR is capillary rise from a shallow water table, ΔSF is the change in subsurface (horizontal) flow of water, and ΔSW is the change in soil water content. All the terms of the equation are expressed in inches or millimeters. The horizontal flow of water in and out of the root zone, CR, DP, and RO may be hard to measure, although DP and RO can be minimized or eliminated with efficient irrigation systems and sound irrigation scheduling. Runoff occurs when water (from irrigation, rain, or melting snow) application rate exceeds soil infiltration rate, particularly in sloping terrain. Given the uncertainties in measuring some of the components of the water balance equation, this method only gives good estimates of ET over longer periods of time, e.g., one week or longer.

ET_c is directly measured using precision weighing lysimeters. However, because of their cost and complex operation, precision weighing lysimeters are limited to use in carefully controlled research settings. In that case, they are used to carefully measure ET_c, often at hourly time steps, but for operational purposes, most often on daily time steps. The results are then used to compute crop coefficient (K_c) values by comparing measured ET_c to computed reference crop ET (ET_{rs}).

$$K_c = ET_c / ET_{rs}$$

Crop coefficients developed in this manner represent the ratio of the ET of a well-watered, actively growing healthy crop to that of the reference crop. Detailed crop coefficient development research has been conducted using this approach in Kimberly, Idaho and Bushland, Texas. There is some uncertainty regarding whether these sets of crop coefficients represent crop growing conditions in the lower Arkansas Valley of Colorado.

Precision weighing lysimeters measure water loss from a control volume by measuring the change in mass with an accuracy of a few hundredths of a millimeter. Non-weighing lysimeters are perhaps more common but they "are not considered suitable for reference ET equation verification and crop coefficient research. They may, however, be very suitable low cost alternatives for studying the effects of varying water salinity levels and high water table conditions on crop ET up and down the Arkansas River Valley" (Ley, 2003).

2. Site Characteristics

The large lysimeter is located at the Colorado State University Arkansas Valley Research Center (AVRC) approximately two miles east of Rocky Ford in Otero County, Colorado (NW1/4 Sec 21, T23S, R 56W). The elevation at the site is approximately 1,274 m, latitude: 38^o 2′ 17.30″ N, and longitude: 103^o 41′ 17.60″ W. See Figure 1.

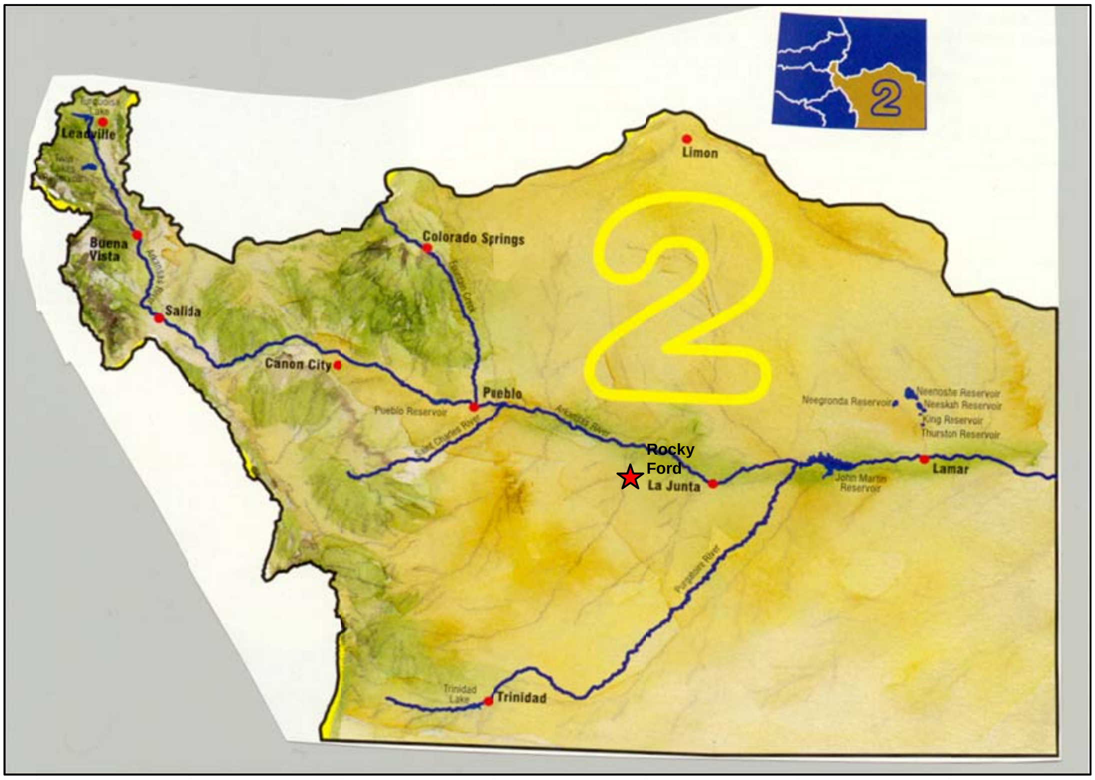

Figure 1. Overview Map of Arkansas River Basin in Southeastern Colorado and location of Rocky Ford, Colo. in the Lower Arkansas Valley

Long-term average monthly climate data for the AVRC are shown in Table 1. The average annual maximum temperature is 21.1°C (70.0°F). The average annual minimum temperature is 2.4°C (36.3°F). The long-term average annual precipitation at the site is 301mm (11.85 inches) with approximately two-thirds of the annual total occurring from May through September. The total average annual snowfall is 589 mm (23.2 inches). The average date of the last spring frost (0°C or 32°F) occurs at about May 1, and the average date of the first fall frost occurs October 5. Thus, the average length of the growing season for warm-season crops like corn is 158 days (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?corock).

Table 1. Period of Record (1/2/1918-12/31/2005) Monthly Climate Summary for Rocky Ford 2SE, Colorado (057167) Climate Station located at the CSU AVRC

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ave. Max. Temperature (C)	7.9	11.2	15.5	20.9	25.8	31.5	34.1	32.8	28.9	22.6	13.8	8.6	21.1
Ave. Max. Temperature (F)	46.3	52.1	59.9	69.6	78.4	88.7	93.4	91.1	84.0	72.7	56.8	47.4	70.0
Ave. Min. Temperature (C)	-10.2	-7.3	-3.6	2.0	7.7	12.7	15.5	14.4	9.3	2.2	-5.0	-9.2	2.4
Ave. Min. Temperature (F)	13.6	18.8	25.6	35.6	45.8	54.8	59.9	57.9	48.8	36.0	23.0	15.4	36.3
Ave. Total Precipitation	8	7	18	31	46	37	50	41	23	20	12	8	301
Ave. Total Precipitation	0.31	0.28	0.72	1.23	1.81	1.44	1.97	1.61	0.92	0.78	0.48	0.3	11.85
Ave. Total SnowFall (mm)	107	84	109	58	5	0	0	0	3	20	91	109	589
Ave. Total SnowFall (in.)	4.2	3.3	4.3	2.3	0.2	0	0	0	0.1	0.8	3.6	4.3	23.2

The soil type at the lysimeter site at Rocky Ford is coarse-loamy, mixed, superactive, mesic Ardic Argiustoll. Selected soil properties are shown in Tables 2 and 3.

Table 2. Soil characteristics of the large lysimeter site

Horizon	Depth (cm)	Textural class	pH water (1:1)	CEC (meq/100) g)	ECe (dS/m)	Total C g/kg	SAR
Ap	0-23	Clay	8.1	17.2	0.82	15.5	1.70
Bt	23-36	Clay	8.0	16.9	0.90	14.8	2.08
Btk	36-100	Loam	8.3	10.0	0.58	9.0	2.46
Bk1	100-170	Loam	8.3	10.9	0.72	9.5	2.40
Bk2	170-230	Clay	8.3	13.5	0.88	10.8	2.18
2C	> 230	Coarse sand	8.7	1.5	-	1.7	-

Table 3. Soil bulk density and hydraulic properties (calculated)

Horizon	Depth	Bulk density	Matric suction in J/kg							Hydraulic conductivity
			1500*	1500	1000	500	100	33	10	
	(cm)	(g/cm^3)	Water content by weight (g/kg)							(cm/hr)
Ap	0-23	1.36	108	123	131	144	182	214	254	0.34
Bt	23-36	1.36	126	124	132	145	182	213	252	0.33
Btk	36-100	1.45	65	77	84	97	134	167	213	1.25
Bk1	100-170	1.43	70	82	89	103	141	176	224	1.06
Bk2	170-230	1.35	110	118	126	141	183	219	266	0.42
2C	> 230	1.86	11	19	22	26	40	53	73	16.9

*Water contents in this column were measured in the laboratory. The soil characterization data were provided by Dr. Lorenz Sutherland, Area Resource Conservationist, La Junta, CO.

3. Lysimeter Description

The large lysimeter was patterned after the lysimeters at Bushland, Texas operated by the USDA-Agricultural Research Service. Marek et al. (1988) provide details of the lysimeter design.

The large lysimeter consists of an inner soil monolith tank with dimensions 3 m x 3 m x 2.4 m deep (10 ft x 10 ft x 8 ft) and an outer containment tank. An enclosed chamber between the two tanks houses the weighing mechanism, the drainage tanks, load cells, and the data loggers as well as standing room for 5-8 people. The inner tank was filled with undisturbed soil (soil monolith, or a deep cross-section of soil to show layers) from an area approximately 107 m (350 ft) from where the lysimeter is located using a pull down frame, hydraulic jacks, and deep soil anchors. The tank plus soil (soil tank) weighed approximately 45.4 Mg (100,000 lbs). Two cranes were required to lift it off the ground and flip it upside down in order to install a drainage system at the bottom of the soil monolith and weld on the monolith tank floor. Approximately four inches of fine sand were added to the bottom of the soil monolith to facilitate water drainage. The soil tank was later moved to its permanent location and set on a steel frame inside the outer tank. The soil monolith tank moves freely within the outer tank and the two are separated at the soil surface by a small gap. The enclosure top, also called the top hat, was welded to the outer tank in situ to ensure a tight fit. The gap between the soil tank and the top hat was covered with a thin PVC material to prevent water from infiltrating the narrow gap between them without restricting the movement of the soil tank. Figures 2-8 are photos of the soil monolith acquisition and lysimeter construction.

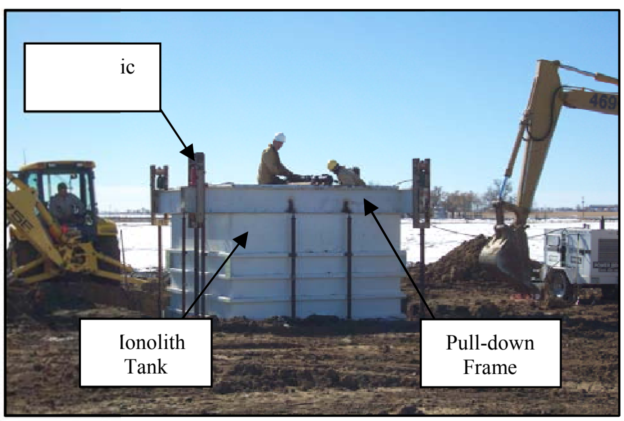

Figure 2. The inner tank being pushed into the ground to acquire the soil monolith
Photo by Dale Straw of the Colo. Division of Water Resources (DWR)

Figure 3. The inner tank plus soil being lifted off the ground prior to moving it to its permanent location *Photo by Abdel Berrada*

Figure 4. The outer tank being lowered into position. The concrete slabs were used to hold the soil in place. They were taken out before re-filling the empty space around the outer tank. *Photo by Dale Straw of DWR*

Figure 5. The inner tank plus soil being lowered inside the containment tank *Photo by Michael Bartolo*

Figure 6. Steel support frame for the soil tank. This photo also shows the scale.

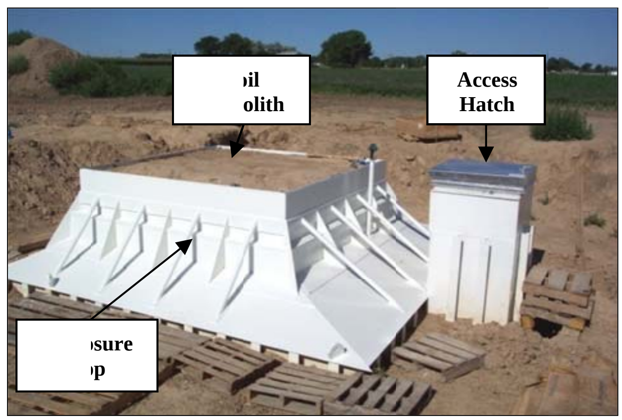

Figure 7. Enclosure top and access entry to the chamber between the inner and outer tanks

Figure 8. View of the large lysimeter after the soil around it was repacked

The weighing mechanism consists of a mechanical lever scale-load cell combination (Fig. 9). The load cell (a device that converts a load into an electronic signal) is connected to a Campbell Scientific CR7 data logger that records the weight of the inner tank plus soil every 2 seconds. Load cell readings are recorded in millivolts per volt (mV/V) and converted to equivalent weight values using load cell calibration results described below. The mechanical lever platform scale has a 100:1 ratio on the counter lever arm. A 50 lb (22.7 kg) load cell is used to measure and record weight changes. For the 100:1 mechanical advantage, the full range of the load cell is a weight change of 5,000 lbs (2270 kg). This is equivalent to 244 mm (9.6 in) depth of water on the lysimeter area. Counterbalance weights on the scale lever arm can easily be adjusted to extend the range of soil monolith tank weight change that may be measured. For practical operational purposes, the full measurement range of the load cell will likely not be utilized to avoid operation at the upper and/or lower limits and potential damage to the load cell.

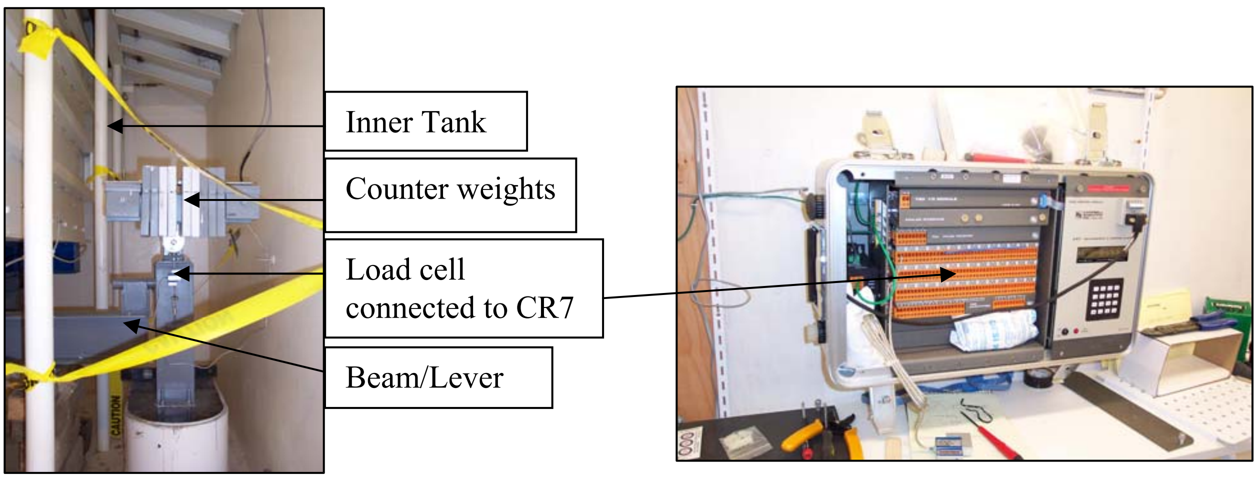

Figure 9. Weighing mechanism and CR-7 *Photos by Dale Straw of DWR*

Meteorological instrumentation readings, including precipitation from rain as measured by a tipping bucket rain gauge mounted on a mast next to the lysimeter, are recorded every six seconds. Data tables of the load cell readings and various combinations of the meteorological sensors are created and output on 5-minute, 15-minute and 24-hour intervals. Examples of load cell and precipitation readings are shown in Figure 10. Water that percolates through the soil monolith is collected in two drainage tanks (Fig. 11) suspended from the scale frame that supports the soil tank, so there is no overall weight change as water drains into the tanks. One tank collects water from the internal portion of the monolith and the other tank collects water from the perimeter of the monolith. Weight of the drainage tanks is recorded using a separate load cell connected to the CR7 data logger.

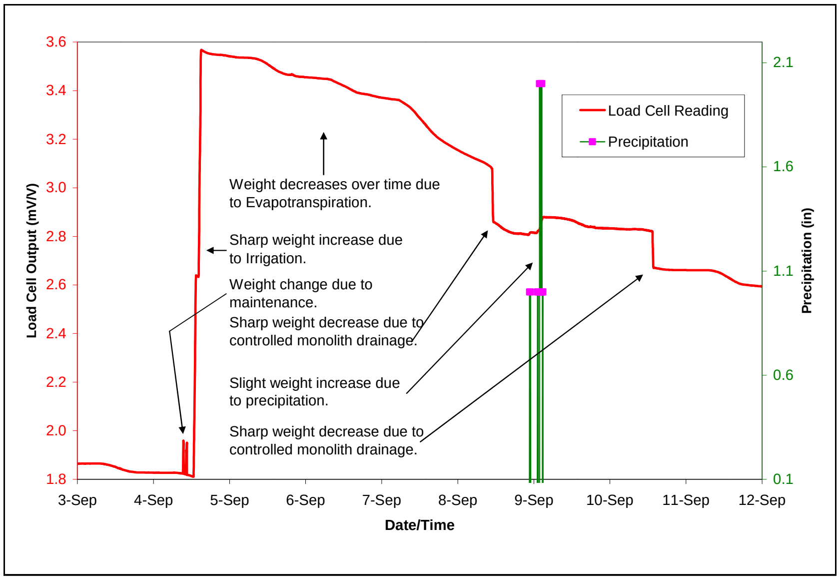

Figure 10. Load cell and precipitation readings for 3-12 September 2006 *Graph by Lane Simmons*

Figure 11. Vacuum pump and drainage tanks
Photo by Dale Straw of DWR

4. Load Cell Calibration

A thorough calibration of the precision weighing mechanism was performed in October 2006 to develop a relationship for converting the load cell output in mV/V to weight in kilograms. The procedure was similar to the one developed and used by USDA-ARS at Bushland, Texas to calibrate similar precision weighing lysimeters at that facility (Howell et al., 1995). The mass in kilograms and number of weights (in parenthesis) used in the calibration procedure were as follows: 320 (9), 22.68 (2), 4.5 (20), 2 (1), 1 (1), 0.5 (1), 0.2 (1), 0.1 (1), and 0.05 (1). Weights were placed on and removed from the surface of the soil monolith in a predetermined order and load cell readings were recorded after the standard deviation of the load cell readings was stabilized following the application or removal of each weight (Fig. 12).

Figure 12. Lysimeter weight calibration

The load cell response was linear from zero to maximum loading and was similar for each set of weight increments as more 320 kg drums were placed on the lysimeter surface (see Tables 1 and 2 in Appendix A). Figure 13 shows the response at the low end of the load cell readings. The slope of the regression line, 685 kg per mV/V, is the coefficient used to convert the change in load cell readings, as the lysimeter gains or loses mass, to the equivalent change in weight of the soil monolith tank. A change of 1 mV/V in the load cell output is equivalent to a water depth change of 76 mm on the lysimeter. Thus, changes in load cell output are simply multiplied by 76 to obtain the amount of water lost through ET or amounts of water gained through precipitation or irrigation. The standard deviation of the weight measurements (accuracy) was less than 0.02%.

After calibration, a 320 kg weight was applied, in turn, to each corner of the soil monolith to check response of the weighing mechanism for effects of uneven loading. No difference in load cell readings was observed for the total soil monolith tank weight as the 320 kg weight was placed in each corner.

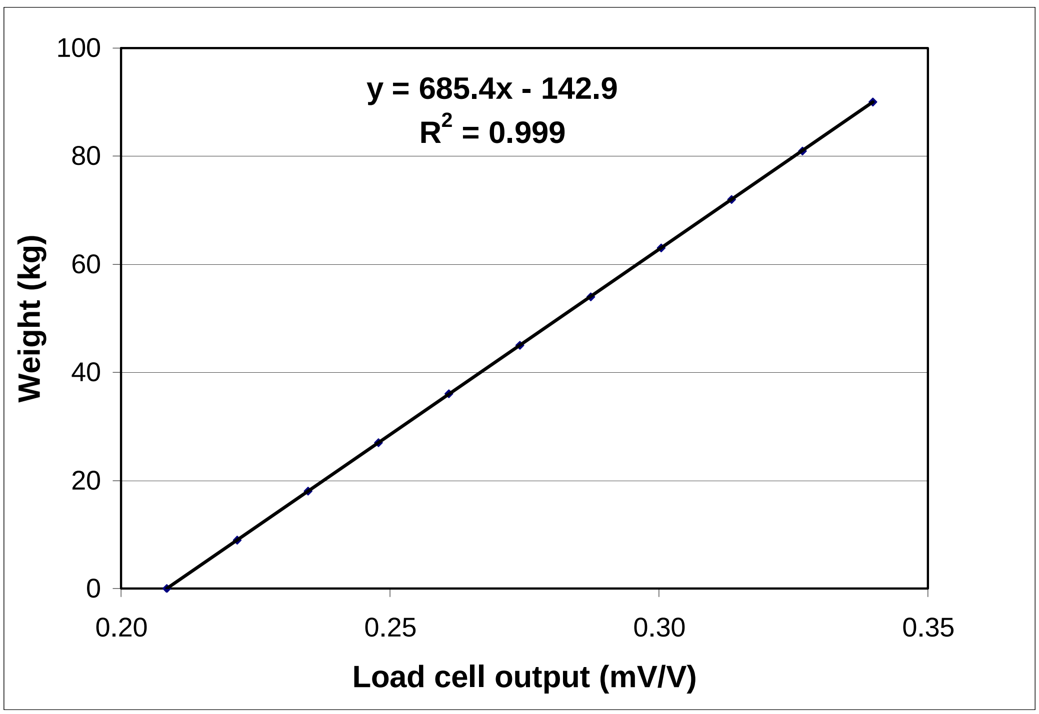

Figure 13. Weight as a function of load cell output
Calibration data analyzed by Dale Straw of DWR

5. Meteorological Instrumentation

Several sensors are used to monitor the atmospheric, crop, and soil conditions above, inside or outside the soil monolith. Sketches showing the location of each sensor are available at AVRC. Some parameters are measured with more than one sensor for comparison or verification purposes. Data from these measurements will be used to compute alfalfa reference evapotranspiration (ET_{rs}) using the ASCE-standardized Penman-Monteith equation (ASCE, 2005).

Weather measurements:

- **Rainfall** (mm) in increments of 0.254 mm (0.01 inch) is measured using a TE525 tipping-bucket rain gauge mounted on a metal post 2 meters above ground.
- **Wind speed** (meters per second) is measured using two instruments: an RM Young Wind Sentry cup anemometer and an RM Young Wind Monitor (propvane).
- **Wind direction** is also measured by the RM Young Wind Monitor (propvane). It is given in degrees where 0 degree = north and 180 degrees = south.
- Ambient **air temperature** (°C) and **relative humidity (**%) are measured using a Vaisala HMP45 sensor located in a mulitplate radiation shield on the sensor mast.
- Ambient **air temperature** (°C), **relative humidity, (**%) and dewpoint temperature (°C) are also measured using a Vaisala HMT331 sensor enclosed in a small cotton region shelter near the lysimeter.
- **Barometric pressure** (millibar) is measured using a Vaisala PTB101B sensor. This is also located in the small cotton shelter.
- **Incoming total shortwave solar radiation** (W m^{-2}) is measured with an Eppley Precision Spectral Pyranometer and a Li-Cor LI200X Pyranometer, both mounted on the radiation instrument stand near the lysimeter.
- **Net radiation** (W m^{-2}) is measured with a REBS Q7 net radiometer mounted on an arm extending over the monolith from the instrument mast.

Crop-related measurements:

- **Surface albedo** (dim.) is found by measuring incoming and reflected radiation using a Kipp and Zonen CM14 Albedometer mounted on an arm extending over the monolith from the instrument mast.
- **Incoming and reflected photosynthetic active radiation** (µmol $s^{-1}m^{-2}$) is measured with a Li-Cor Quantum sensor mounted on the radiation stand and mounted inverted on an arm extending over the monolith from the instrument mast, respectively.
- **Incoming photosynthetic active radiation** (µmol $s^{-1}m^{-2}$) transmitted through the crop canopy to the soil surface is measured using two Li-Cor Line Quantum sensors located on the monolith surface.
- **Surface temperature** (°C) is measured using two precision infrared thermometers (IRT) located over the monolith. One IRT measures the temperature of the target's surface (crop canopy) at an oblique angle and the other measures the temperature of the target's surface straight down (nadir). Both sensors are mounted on an arm extending over the monolith from the instrument mast. The temperature of the body of each sensor is also measured and used to correct the surface temperature.

Soil measurements:

- **Soil Temperature** (°C) is measured with direct burial copper-constantan thermocouples, or junctions between different metals that produce a voltage related to a temperature difference. There are 14 temperature sensors located inside the soil tank and six outside. Of the monolith sensors, four replications of shallow soil temperatures (four at 10 mm below the soil surface and four at 40 mm below the surface) are used in combination with heat flux plates to estimate soil heat flux. There are two replications of deep soil temperature measurements: at 0.5 m, 1 m, 2 m depths in both the soil monolith and in the exterior field approximately 4.5 - 6 m from the monolith.

- **Soil Heat Flux** (W m^{-2}), the amount of heat moving in or out of the soil, is measured with heat flux plates placed at 100 mm depth below the surface of the monolith. There are four replications: two are in the 3rd furrow and two are in the 3rd full bed from the west edge of the monolith tank. The heat flux plates are placed vertically below the shallow (10 mm and 40 mm) soil temperature sensors and used in combination with the shallow soil temperature measurements described above to estimate soil heat flux.
- **Soil Moisture**: Two 38 mm (1.5 in) diameter electromechanical steel tubes (EMT) were installed in the soil monolith (Figure 14) and four outside the monolith (one in each compass direction) to a depth of 2 m. A CPN 503DR neutron probe is used to measure soil water content (% by volume) at 10, 30, 50, 70, 90, 110, 130, 150, 170, and 190 cm depths in the soil profile.

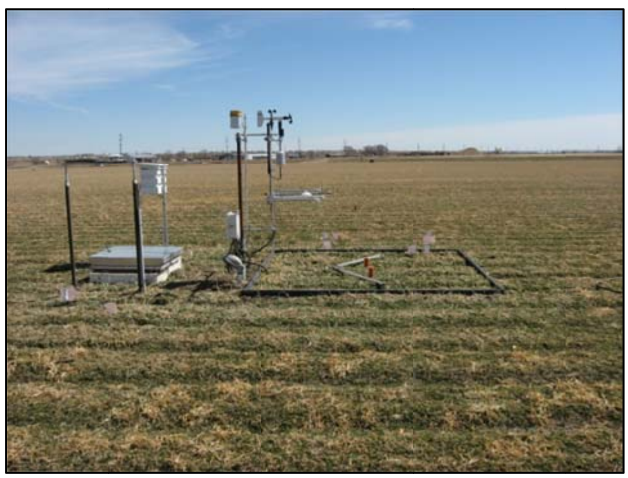

Figure 14. Neutron probe access tube placement in the soil monolith after it was seeded to alfalfa. The tops of the access tubes are covered with capped PVC pipes painted in orange. The white flags mark the location of various sensors. Two Li-Cor Line Quantum sensors are visible on the soil monolith surface.

6. Calibration of the Neutron Probe

The CPN 503DR Hydroprobe operates by emitting radiation from an encapsulated radioactive source, Americium-241:Beryllium. The high-energy neutrons emitted from the radioactive source are moderated (slowed down) by collisions with atoms in the soil. Only the low-energy, moderated neutrons are detected by the Helium-3 detector, and the data is displayed on the surface of an electronic assembly board as counts per unit-time or another unit of interest, such as inches of water per foot of soil. The display board is integral to the source shield assembly, which also includes a cable and a shield box (503 DR Hydroprobe Moisture Gauge Operating Manual, CPN International, INC., Martinez, CA). Hydrogen (H) is “by far the most effective element for slowing neutrons, and because rapid changes in soil H content are almost completely due to changes in soil water content, the count of slow neutrons is proportional to soil water content.” (Evett et al., 2003). The probe is lowered into an access tube to assess soil water content at various depths. The CPN 503DR Hydroprobe comes with a laboratory calibration to convert slow neutron count into soil water content. Field calibration is recommended since the laboratory calibration only uses two data points (wet and dry) and the measurements are done in a sand media. A separate calibration should also be done for neutron probe readings at depths less than (<) 30 cm from the soil surface due to the potential loss of neutrons to the air. For the early neutron probe designs, Evett et al. (2003) reported that the majority of slow neutrons were measured from a nearly spherical volume of 20-cm (saturated soil) to 40-cm (dry soils) in radius. The CPN 503DR probe was calibrated in 2007 based on the method developed by Evett et al. (2003). Two sets of 2.5-m (98-in) long, 38-mm (1.5-in) inside diameter electromechanical steel tubes (EMT) were installed in the fallow ground next to the lysimeter field on 23 August 2007. Each set consisted of three tubes approximately 1.8 m apart. The two sets were labeled ‘dry’ and ‘wet’ and were separated by about 9.1 m of fallow ground. Shortly before installing each access tube, a hole was drilled in the ground with a hydraulic probe fitted with a 41-mm (1.625-in) outer diameter (O.D.) soil tube. The distal end of each access tube was crimped to facilitate its insertion into the hole. The hole was about the same size as the O.D. of the access tube; therefore, it was necessary to push the tube into the hole by tapping with a hammer on a wood block placed on top of the tube. This ensured a tight fit between the outside wall of the access tube and the soil. Both ends of the access tube were plugged with rubber stoppers to prevent water and debris from entering the tube. Each tube extended 15 cm above the soil surface. A depth control stand as described by Evett et al. (2003) was built and used when measuring soil water content with the neutron probe, i.e., to ensure that the measurements are made at the same depth relative to the soil surface (Fig. 15).

Figure 15. The neutron probe CPN 503DR sitting on top of the depth-control stand
Photo by Lane Simmons

After installing the access tubes, an area of approximately 2.5 m x 6 m surrounding the wet set was diked (surrounded with a dike to prevent water escape or flooding) and ponded with water on 24 August 2007 (Fig. 16). Additional water was added on 4 September and 7 September to create high soil water conditions and to differentiate the 'wet' set from the 'dry' set (to which no water was added). On 11 September, a trench was dug next to the access tubes in the dry set with a back-hoe to facilitate soil sampling. The few inches of soil closest to each tube were trimmed with a shovel to expose the front side of the tube. In order to minimize soil water loss by evaporation, only a few feet of tube were exposed at a time and soil samples were taken shortly thereafter. The tube was marked with a permanent marker at 10, 30, 50, 70, 90, 110, 130, 150, 170, and 190 cm below the soil surface (Fig. 17). Soil samples were then taken with the Madera Probe (Fig. 18) at two locations above and two locations below (on each side of the tube) each depth. The soil samples (60 cm^3 per sample) were stored in zip-close bags for ease of use and tare (packaging) weight uniformity. The next day, soil samples were taken from the wet set using the same procedure. A total of 240 soil samples (3 tubes/set x 2 sets x 10 depths/tube x 4 samples/depth) were collected.

Figure 16. Water being added to the 'wet' set of neutron probe access tubes. The 'dry' set is in the background. *Photo by Lane Simmons*

Figure 17. Measuring soil depth before taking soil samples *Photo by Kevin Tanabe*

Figure 18. Soil sampling with the Madera Probe *Photos by Michael Bartolo.*

The samples were weighed within one-two hours of sampling and left to dry in the greenhouse (with the zip-close bags open) for several days before transferring the soil to steel cans and drying them in the oven for eight hours at 105 ^{o}C. (Drying time was adequate since the soil was already nearly dried by the time it was transferred to the steel cans.) The empty weights of the zip-close bags, the steel cans, and the fresh and oven-dry (OD) weights of the soil were recorded. Note: It would have been easier to use steel cans from the start, but there were not enough cans or lids.

The water content of each soil sample was calculated as follows:

Soil water content on a mass basis:

$$\theta_m \text{ (g g}^{-1}\text{)} = [(\text{soil fresh weight} - \text{tare}) - (\text{soil OD weight} - \text{tare})]/(\text{soil OD weight} - \text{tare})$$

The weights are in grams (g).

Soil bulk density:

ρ (g cm^{-3}) = (soil OD weight (g) – tare (g)) / 60 (cm^3)

Volumetric soil water content:

θ_v (cm^3 cm^{-3}) = θ_m x (ρ/ρ_w) where, ρ_w = 1 g cm^{-3} at 4 ^{o}C (density of pure water)

Water depth per 20-cm soil depth:

D (cm/20 cm of soil depth) = θ_v x 20 cm

In order to calculate the amount of water per volume of soil, D is multiplied by the surface area, which for the large lysimeter = 3 m x 3 m or 9 x 10^4 cm^2. The amount of water available to the plants is the total amount of water measured by the neutron probe or the lysimeter minus soil water content at what is commonly referred to as the 'wilting point.' The wilting point is the lower water availability limit at which the plant can no longer extract water from the soil and thus wilts. The upper limit is 'field capacity,' or the amount of water the soil can hold with no drainage (below the depth of interest) occurring. Therefore, available water equals water content at field capacity minus water content at wilting point. Water content at the wilting point is often estimated from laboratory measurements where the water remaining in the soil after a pressure of 1500 J/kg was applied to it is measured.

Prior to digging the trench to expose the access tubes, neutron probe readings were taken with CPN 503DR at the 10-, 30-, 50-, 70-, 90-, 110-, 130-, 150-, 170-, and 190-cm soil depths. The probe assembly was set on top of the depth-control stand and a four-minute standard reading was taken. The probe was then lowered into the access tube and a one-minute reading was taken at each depth. The procedure was repeated for each access tube.

The measured volumetric soil water content was regressed against the neutron probe count ratio (CR) to obtain the calibration equation later used to convert CR into water content. The CR is the ratio of the slow neutron count at a given soil depth over the average standard count. The soil water and neutron probe data collected for calibration are given in Tables 3-6 of Appendix A. Outliers and "bad" samples were discarded from the regression analysis. The correlation between water content and CR was highest for the 10-cm depth (Fig. 19a) and lowest, but still significant, for the 110- to 190-cm depth (Fig. 19d). For practical purposes, calibration equation (1) should be used for the shallow-depth reading and equation (2) for readings at or below 30 cm (see below).

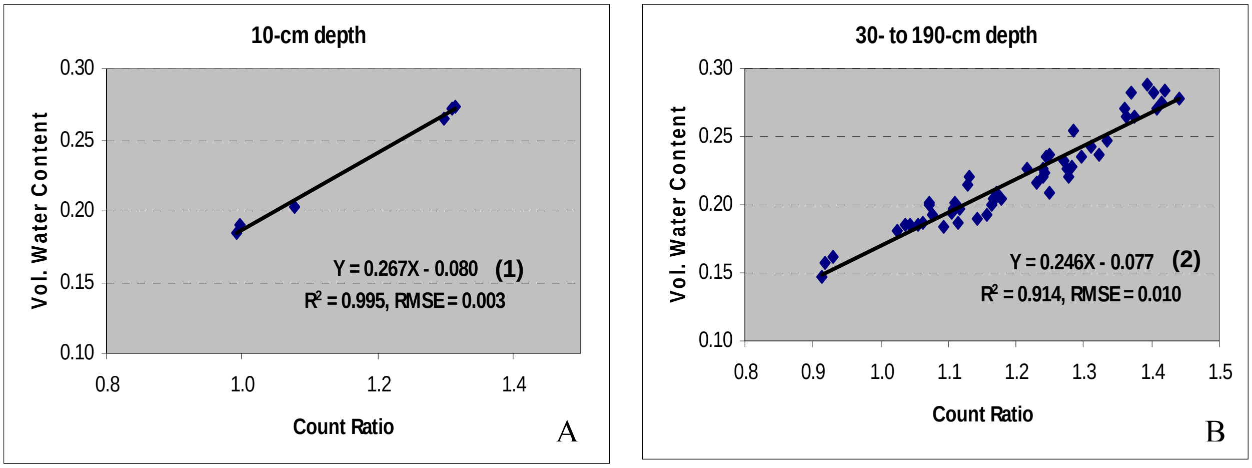

Figure 19a. Volumetric soil water content (cm^3/cm^3) as a function of the CPN 503DR neutron probe count ratio at the (A) 10-cm and (B) 30- to 190-cm depths

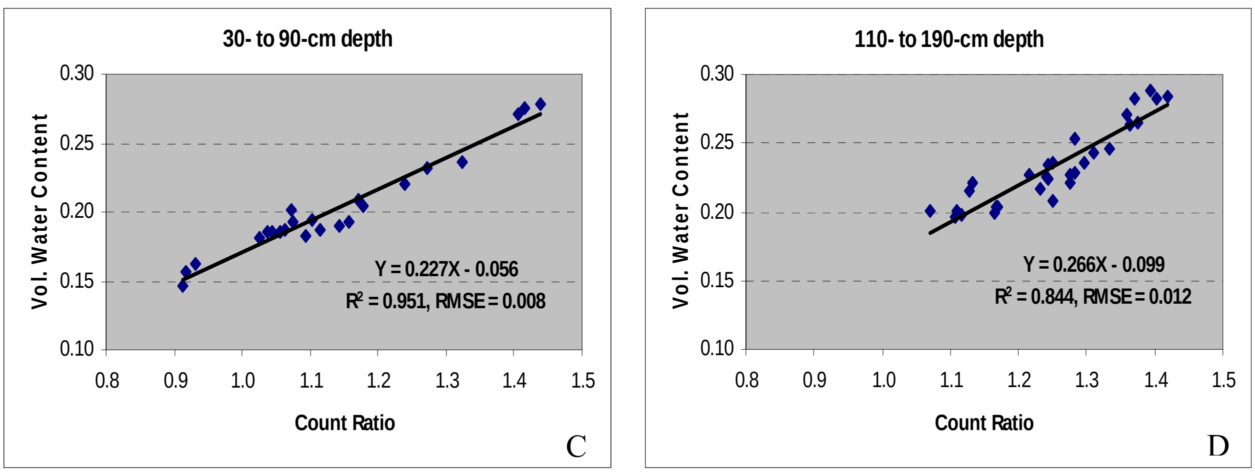

Figure 19b. Volumetric soil water content (cm^3/cm^3) as a function of the CPN 503DR neutron probe count ratio at the (C) 30- to 90-cm and (D) 110- to 190-cm depths

Y is volumetric soil water content in cm^3/cm^3 and X is count ratio. To express Y in cm of water per 20 cm of soil depth, the following equations should be used:

1) Upper 20 cm of soil:

$$Y\ (cm/20cm) = 5.323\ X - 1.578,\ R^2 = 0.995$$

2) Lower depths:

$$Y\ (cm/20\ cm) = 4.936\ X - 1.541,\ R^2 = 0.915$$

In comparison, the laboratory calibration equation provided by CPN International, Inc. (Table 4) is:

Y (in/ft) = 1.984 X – 0.090 or Y (**cm/20cm**) = 3.307 X – 0.150, R^2 = 1

Table 4. CPN 503DR factory calibration (CPN International, Inc.)

Water content		1-min	Standard	Count
In/ft	cm/20cm*	Count	Count	Ratio
0	0	309	6814	0.045
4.025	6.708	14161	6828	2.074

*Converted from column 1

The two access tubes were installed in the lysimeter monolith on October 11, 2007 using the so-called auger-from-within method. This procedure required the use of a step ladder, plywood platform, hammer, level, and a striking block. A shallow pilot hole was dug; the tube was then placed in the hole, and the Edelman auger was inserted down through the tube. Care was taken to ensure that the tube was plumb during the first one-third of the tube's installation. Soil was augered and removed from the hole, and the access tube was pushed down in approximately 15-cm increments until the tube was set on the tank floor. One tube was placed at 1.15 m from the east wall and the other 1.15 m from the west wall. Care was taken to avoid the vacuum drainage system in the bottom of the tank. The four access tubes outside the lysimeter were installed on October 23, 2007 using the same procedures. Each tube was aligned with a monolith centerline and placed on a bed. Each tube is situated approximately 9 m from the north, south, east, or west side of the monolith.

Soil water content readings will be taken before and after (e.g., 48 hours after) each irrigation, and at the beginning and end of each growth period. Comparisons of the soil water content inside and outside the soil monolith will be used in an effort to maintain similar soil water conditions in the monolith and the surrounding field.

7. Soil Preparation

Shortly after the installation of the large lysimeter in 2006, the ground around it was flooded to settle the soil. Later, the ground was ripped with a Big Ox chisel plow to alleviate compaction, then plowed, disked, leveled, furrowed, and rolled. The distance between furrows is 76 cm (30 inches), which is common in the Arkansas Valley. The top 20 cm of the monolith were tilled with a rotary tiller, also called a rototiller, and the beds and furrows were prepared with shovels and spades. There are three full beds in the middle, a half-bed against the eastern and western edges of the monolith, and four furrows. They are aligned with the beds and furrows outside the monolith and run north-south.

The total field area surrounding the large lysimeter to ensure good fetch is approximately 4 ha (10 acres: 520 ft x 840 ft), of which 2.4 ha (6 acres) were fallowed since 2005 and an adjacent 1.6 ha (4 acres) was in alfalfa since 2003. It was paramount to get all 4 ha managed uniformly, so in early spring 2007, the area in alfalfa was sprayed with Roundup and the whole field was planted to oats on 5 April 2007 at 157 kg/ha (140 lb/acre). The oat crop inside and outside the monolith was irrigated four times and cut for hay on 25 June 2007. Figure 20 shows the lysimeter after the oat crop was cut.

Figure 20. View of the lysimeter and meteorological instrumentation in late June 2007 *Photo by Michael Bartolo*

The hay was baled on 2 July 2007 and the bales removed shortly after that. Oats were chosen as the first crop to be planted after the installation of the large lysimeter because they are easy to grow and could be planted and harvested early, allowing enough time for soil preparation and the seeding and establishment of the next crop (alfalfa) before fall dormancy.

In the latter part of July, the soil in the lysimeter field was again ripped, disked, and leveled. Alfalfa variety 'Genoa' was seeded on 9 August 2007 at 21 kg/ha (19 lb/acre) and the field was then furrowed and rolled. The soil inside the monolith was prepared and seeded by hand. The number and arrangement of beds and furrows was the same as with the oat crop. Two hundred and twenty-five (225) kg/ha (200 lbs) of 11-52-0 per acre were broadcast on top of the hay crop on 6 December 2007.

Alfalfa establishment inside and outside the monolith was good to excellent with the exception of a couple of acres approximately 30 m west of the lysimeter. In this area, the alfalfa stand was spotty due to a heavy infestation of morning glory. The whole field was mowed with a brush hog on 27-28 September 2007 above the hay crop to suppress the taller weeds. At that time it became clear that approximately half of the area west of the lysimeter would have to be reseeded in the spring of 2008 to achieve a more uniform stand with the rest of the field. Alfalfa was irrigated on 17 August, 4 September, and 4 October 2007. Water from the irrigation canal was dispensed to each furrow with a siphon.

8. Irrigation of the Soil Monolith

The monolith was irrigated at the same time as the surrounding field area. The amount of water applied was determined by subtracting the volume of furrow outflow (flow x duration) from the volume of furrow inflow of adjacent furrows using V-shaped furrow flumes. Water was pumped from the irrigation canal and applied to the monolith through a hose fitted with a flow meter and a valve. The furrows on the monolith were filled with water to simulate normal flood irrigation (Fig. 21).

Figure 21. Water being applied to the soil monolith *Photo by Michael Bartolo*

Ideally, the crop in the monolith should be irrigated the same way as the rest of the field, i.e., water flowing in and out of the furrows over the time it takes to replenish the root zone to field capacity. To do this, one would have to cut slots in the section of the walls of the inner and outer tanks that protrude above ground level to provide continuity in the furrows and water flow inside and outside the monolith. Another solution would be to pump water in and out of the furrows inside the monolith in the same proportion as what occurs in the furrows immediately outside the monolith. Both solutions were judged impractical. Another option that was contemplated was to irrigate the lysimeter field with a linear-move sprinkler system, which would allow for uniform irrigation inside and outside the monolith. This option was put on hold due to the cost of the sprinkler system in addition to the fact that over 90% of the crop land in the Arkansas Valley is furrow-irrigated.

9. Future Plans

Alfalfa in the large lysimeter field will be maintained for at least three more years to serve as a check of the ASCE Std. Reference ET Equation and to develop alfalfa crop coefficients. After that, the field will be planted to other major crops in the Arkansas Valley (corn, wheat, sorghum, onions, etc.) to determine their crop coefficients. It will take at least two years of data per crop to generate reliable K_c estimates.

The reference lysimeter, 1.5 m x 1.5 m x 2.4 m (5 ft x 5 ft x 8 ft) in size, was installed in 2009 in an adjacent field. The reference lysimeter will be initially planted to oats to reduce or eliminate soil settling and field variability during the construction period.

The lysimeter project is a joint effort between CWCB, the Colorado Division of Water Resources (DWR), and CSU. Support has also been provided by U.S. Department of Agriculture

– Agricultural Research Service (USDA-ARS) engineers and scientists in Fort Collins, Colorado and Bushland, Texas.

References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. "Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements." *FAO Irrigation and Drainage Paper 56.* Rome, Italy.

ASCE-EWRI. 2005. "The ASCE Standardized Reference Evapotranspiration Equation". Edited by R.G. Allen, I.A. Walter, R.E. Elliott, T.A. Howell, D. Intenfisu, M.E. Jensen, and R. L. Snyder. Task Committee on Standardization of Reference Evapotranspiration of EWRI. Amer. Society of Civil Engineers, Reston, VA.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2003. "A depth control stand for improved accuracy with the neutron probe." *Vadoze Zone Journal* 2: 642-649. Soil Sci. Soc. of America, Madison, WI.

Howell, T.A., A.D. Schneider, D.A. Dusek, T.H. Marek, and J.L. Steiner. 1995. "Calibration and Scale Performance of Bushland Weighing Lysimeters." *Transactions of the ASCE,* Vol 38(4):1019-1024. American Society of Agricultural Engineers, St. Joseph, MI.

Jensen, M.E., R.D. Burman, and R.G. Allen, Eds. 1990. *Evapotranspiration and Irrigation Water Requirements.* ASCE Manual No. 70. New York, N.Y.

Ley, T.W. 2003. *Lysimeters for Evapotranspiration Research in the Arkansas River Valley*. Colorado Division of Water Resources.

Littleworth, A. L. 2003. "Fourth Report of the Special Master." *State of Kansas vs. State of Colorado and the United States of America*. No. 105, Original. Supreme Court of the United States. October.

Marek, T.H., A.D. Schneider, T.A. Howell, and L.L. Ebeling. (1988). "Design and construction of large weighing monolithic lysimeters." *Trans. ASAE,* 31(2): 477-484.

Publications

Andales, A.A., A. Berrada, L. Simmons, M. Bartolo, D. Straw, and T. Ley. 2008. *Performance of the ASCE Standardized Reference ET Equation in the Arkansas Valley of Colorado.* 2008 Joint ASA CSSA GSA HGS GCAGH SSSA Annual Meetings. 5-9 October 2008, Houston, TX.

Bartolo, M, D. Straw, and B. Schafer. 2006. "Update on the construction of the weighing lysimeter in the Arkansas Valley." *Colorado Water* 24(6):14.

Bartolo, M, D. Straw, and B. Schafer. 2008. "Update on the construction of the weighing lysimeter in the Arkansas Valley." In *Arkansas Valley Research Center 2006 Reports*, CSU Ag. Expt. Station Technical Report 08-14. 43-46.

Berrada, A., L. Simmons, M. Bartolo, D. Straw, and T. Ley. 2008. "The Lysimeter Project in Rocky Ford: Objectives and Accomplishments." *Colorado Water* 25 (1) : 8-12, Newsletter of the Water Center of Colorado State University, Jan./Feb. 2008, Ft. Collins, CO.

Presentations

Lower Arkansas Valley Water Conservation District Meeting, October 18, 2006, Rocky Ford
Colorado Water Conservation Board Meeting and Tour, May 16, 2006, Rocky Ford
East Otero Conservation Dist. Meeting, February 5, 2007, Rocky Ford
Arkansas Valley Roundtable Lysimeter Presentation, February 7, 2007, Pueblo
Arkansas Valley Roundtable Lysimeter Presentation, February 14, 2007, Pueblo
Arkansas River Basin Tour, April 12, 2007, Rocky Ford
Lower Arkansas Valley Water Conservancy District Tour, July 18, 2007, Rocky Ford
Colorado Agriculture Leadership Tour, September 27, 2007, Rocky Ford
CRWWI Board Meeting Lysimeter Presentation, November 16, 2007, Denver
Arkansas Valley Roundtable Research Presentation, December 11, 2007, Rocky Ford
Colorado Water Congress, January 25, 2008, Denver
Irrigation and Nutrient Management Workshop, January 30, 2008, Rocky Ford
East Otero Conservation District Meeting, February 4, 2008, Rocky Ford
Farm, Ranch, and Water Symposium, February 7, 2008, Rocky Ford
Colorado Agriculture Big and Small Conference, February 22, 2008, Greeley
Lysimeter Field Tour, August 6, 2008, Rocky Ford
AVRC Biennial Field Day, September 4, 2008, Rocky Ford
NRCS-Regional Meeting, October 31, 2008, La Junta
Lower Arkansas Valley Water Conservancy District Board Meeting, November 19, 2008, Rocky Ford
Farm, Ranch, and Water Symposium, February 5, 2009, Rocky Ford
Colorado Agriculture Big and Small Conference, February 20, 2009, Greeley

Appendix A

Table 1. Load cell response to the addition or removal of 9-kg weights*

Load-cell output mV/V	Weight Kg	Regression analysis	
0.20853	0	Slope	684.9324864
0.22154	9	Intercept	-142.8175164
0.23476	18	Correlation	0.999997256
0.24789	27	R-square	0.999994512
0.26098	36		
0.27412	45		
0.28727	54		
0.30042	63		
0.31350	72		
0.32668	81		
0.33980	90		
0.34003	90		
0.32695	81		
0.31367	72		
0.30065	63		
0.28741	54		
0.27426	45		
0.26112	36		
0.24799	27		
0.23474	18		
0.22185	9		
0.20853	0		

*Two 4.5 kg ammo cans or the equivalent of 1.0 mm of water on the lysimeter surface.

Table 2. Load cell response to the addition or removal of 9-kg weights when there were three (Col. 2) or six (Col. 4) 320-kg drums on top of the monolith

(1) Load-cell output mV/V	(2) Weight Kg	(3) Load-cell Output mV/V	(4) Weight Kg	Regression analysis (Col. 1 & 2)	
1.61345	960	3.01645	1920	Slope	685.0095045
1.62685	969	3.02965	1929	Intercept	-145.5030427
1.63990	978	3.04290	1938	Correlation	0.999987745
1.65310	987	3.05610	1947	R-square	0.999975491
1.66620	996	3.06920	1956		
1.67935	1005	3.08230	1965		
1.69250	1014	3.09550	1974	Regression analysis (Col. 3 & 4)	
1.70560	1023	3.10865	1983	Slope	684.9472575
1.71880	1032	3.12180	1992	Intercept	-146.2098185
1.73195	1041	3.13495	2001	Correlation	0.999994201
1.74515	1050	3.14815	2010	R-square	0.999988403
1.74535	1050	3.14785	2010		
1.73225	1041	3.13440	2001	Average slope from Tables 1&2	
1.71910	1032	3.12165	1992		684.9630828
1.70590	1023	3.10865	1983		
1.69290	1014	3.09570	1974		
1.67980	1005	3.08225	1965		
1.66655	996	3.06900	1956		
1.65350	987	3.05605	1947		
1.64040	978	3.04300	1938		
1.62725	969	3.02970	1929		
1.61410	960	3.01660	1920		

Table 3. Neutron probe field calibration—Soil data for the ‘dry’ set

Access Tube	Sample No.	Depth (cm)	Tare (g)	Fresh Weight Net (g)	O.D. Weight w/tare (g)	Water Content (g/g)	Bulk Density (g/cc*)	Water Content (cc/cc)
A	1	10	64.7	77.2	134.9	0.100	1.170	0.117
A	2	10	65.8	82.2	141.7	0.083	1.265	0.105
A	3	10	65.1	110.5	160.3	0.161	1.587	0.255
A	4	10	64.4	110.3	159.4	0.161	1.583	0.255
A	1	30	64.4	114.3	163.1	0.158	1.645	0.260
A	2	30	65.0	105.7	156.0	0.162	1.517	0.245
A	3	30	65.5	109.5	161.3	0.143	1.597	0.228
A	4	30	64.1	98.4	149.8	0.148	1.428	0.212
A	1	50	64.7	107.6	158.9	0.142	1.570	0.223
A	2	50	80.5	109.7	175.9	0.150	1.590	0.238
A	3	50	65.8	99.8	155.6	0.111	1.497	0.167
A	4	50	64.8	99.5	154.3	0.112	1.492	0.167
A	1	70	65.1	94.2	149.9	0.111	1.413	0.157
A	2	70	65.2	90.4	146.8	0.108	1.360	0.147
A	3	70	65.1	94.7	150.4	0.110	1.422	0.157
A	4	70	65.7	93.9	149.6	0.119	1.398	0.167
A	1	90	65.1	93.1	147.9	0.124	1.380	0.172
A	2	90	65.5	93.8	148.6	0.129	1.385	0.178
A	3	90	64.7	94.2	148.1	0.129	1.390	0.180
A	4	90	65.1	93.6	147.1	0.141	1.367	0.193
A	1	110	68.7	91.6	150.8	0.116	1.368	0.158
A	2	110	65.1	94.1	146.7	0.153	1.360	0.208
A	3	110	74.5	96.0	159.7	0.127	1.420	0.180
A	4	110	64.6	95.6	147.5	0.153	1.382	0.212
A	1	130	65.4	97.6	151.1	0.139	1.428	0.198
A	2	130	65.4	100.3	154.1	0.131	1.478	0.193
A	3	130	65.3	100.1	153.3	0.138	1.467	0.202
A	4	130	65.5	100.1	153.0	0.144	1.458	0.210
A	1	150	65.6	98.1	152.5	0.129	1.448	0.187
A	2	150	64.9	102.3	155.0	0.135	1.502	0.203
A	3	150	65.5	100.8	153.0	0.152	1.458	0.222
A	4	150	65.4	98.8	151.9	0.142	1.442	0.205
A	1	170	71.4	96.0	153.3	0.172	1.365	0.235
A	2	170	64.8	94.9	147.0	0.155	1.370	0.212
A	3	170	69.8	93.7	149.5	0.176	1.328	0.233
A	4	170	65.0	98.0	147.5	0.188	1.375	0.258
A	1	190	65.4	100.1	149.1	0.196	1.395	0.273
A	2	190	64.4	98.8	147.6	0.188	1.387	0.260
A	3	190	73.6	98.1	156.1	0.189	1.375	0.260
A	4	190	74.4	101.6	158.6	0.207	1.403	0.290
B	1	10	65.5	81.9	139.2	0.111	1.228	0.137
B	2	10	84.8	74.8	153.2	0.094	1.140	0.107
B	3	10	64.6	109.3	159.3	0.154	1.578	0.243

Table 3 (Continued)

Access Tube	Sample No.	Depth (cm)	Tare (g)	Fresh Weight Net (g)	O.D. Weight w/tare (g)	Water Content (g/g)	Bulk Density (g/cc)	Water Content (cc/cc)
B	4	10	64.4	111.2	160.4	0.158	1.600	0.253
B	1	30	65.3	108.0	159.3	0.149	1.567	0.233
B	2	30	65.3	108.7	159.9	0.149	1.577	0.235
B	3	30	65.4	107.8	159.5	0.146	1.568	0.228
B	4	30	65.0	107.1	158.3	0.148	1.555	0.230
B	1	50	65.4	104.8	157.5	0.138	1.535	0.212
B	2	50	64.9	104.5	156.1	0.146	1.520	0.222
B	3	50	65.4	100.7	155.6	0.116	1.503	0.175
B	4	50	69.8	103.8	161.6	0.131	1.530	0.200
B	1	70	65.6	91.9	148.4	0.110	1.380	0.152
B	2	70	65.5	93.2	150.3	0.099	1.413	0.140
B	3	70	65.1	91.8	147.8	0.110	1.378	0.152
B	4	70	65.5	89.3	146.1	0.108	1.343	0.145
B	1	90	64.9	90.7	144.9	0.134	1.333	0.178
B	2	90	64.8	96.0	149.4	0.135	1.410	0.190
B	3	90	84.2	89.1	163.1	0.129	1.315	0.170
B	4	90	64.9	95.6	148.2	0.148	1.388	0.205
B	1	110	65.4	66.2	122.7	0.155	0.955	0.148
B	2	110	64.2	98.6	149.5	0.156	1.422	0.222
B	3	110	64.6	97.5	148.9	0.157	1.405	0.220
B	4	110	65.2	96.2	148.2	0.159	1.383	0.220
B	1	130	84.1	98.1	170.8	0.131	1.445	0.190
B	2	130	65.6	95.8	150.2	0.132	1.410	0.187
B	3	130	65.6	87.3	142.1	0.141	1.275	0.180
B	4	130	65.7	99.1	152.4	0.143	1.445	0.207
B	1	150	64.6	102.1	155.0	0.129	1.507	0.195
B	2	150	64.9	103.4	156.2	0.133	1.522	0.202
B	3	150	64.9	100.4	153.2	0.137	1.472	0.202
B	4	150	80.9	96.2	165.0	0.144	1.402	0.202
B	1	170	64.1	99.8	149.5	0.169	1.423	0.240
B	2	170	65.8	93.2	145.3	0.172	1.325	0.228
B	3	170	64.7	100.5	149.5	0.185	1.413	0.262
B	4	170	65.0	101.6	152.0	0.168	1.450	0.243
B	1	190	65.2	103.4	151.7	0.195	1.442	0.282
B	2	190	64.3	101.1	147.8	0.211	1.392	0.293
B	3	190	64.5	102.2	148.9	0.211	1.407	0.297
B	4	190	72.0	97.9	153.1	0.207	1.352	0.280
C	1	10	64.0	89.9	146.5	0.090	1.375	0.123
C	2	10	65.3	83.3	141.8	0.089	1.275	0.113
C	3	10	64.5	114.7	163.5	0.159	1.650	0.262
C	4	10	64.2	116.0	164.5	0.157	1.672	0.262
C	1	30	65.7	110.1	161.7	0.147	1.600	0.235
C	2	30	65.3	106.4	157.9	0.149	1.543	0.230

Table 3 (Continued)

Access Tube	Sample No.	Depth (cm)	Tare (g)	Fresh Weight Net (g)	O.D. Weight w/tare (g)	Water Content (g/g)	Bulk Density (g/cc)	Water Content (cc/cc)
C	3	30	65.1	99.8	152.7	0.139	1.460	0.203
C	4	30	65.5	99.4	152.0	0.149	1.442	0.215
C	1	50	64.8	103.7	155.9	0.138	1.518	0.210
C	2	50	65.2	102.1	154.7	0.141	1.492	0.210
C	3	50	80.5	99.1	169.4	0.115	1.482	0.170
C	4	50	64.8	100.0	154.1	0.120	1.488	0.178
C	1	70	65.1	93.9	149.5	0.113	1.407	0.158
C	2	70	73.0	92.7	156.1	0.116	1.385	0.160
C	3	70	64.9	94.0	148.9	0.119	1.400	0.167
C	4	70	64.9	95.1	150.3	0.114	1.423	0.162
C	1	90	77.4	97.1	162.7	0.138	1.422	0.197
C	2	90	64.8	94.7	148.6	0.130	1.397	0.182
C	3	90	65.7	95.8	149.7	0.140	1.400	0.197
C	4	90	76.3	92.4	156.9	0.146	1.343	0.197
C	1	110	70.5	94.3	153.0	0.143	1.375	0.197
C	2	110	65.2	96.3	149.0	0.149	1.397	0.208
C	3	110	72.9	90.3	150.4	0.165	1.292	0.213
C	4	110	75.6	96.1	158.1	0.165	1.375	0.227
C	1	130	73.7	90.5	153.2	0.138	1.325	0.183
C	2	130	64.9	94.5	147.5	0.144	1.377	0.198
C	3	130	70.4	92.6	151.3	0.145	1.348	0.195
C	4	130	64.9	99.2	151.4	0.147	1.442	0.212
C	1	150	64.6	99.3	152.5	0.130	1.465	0.190
C	2	150	65.1	96.9	150.1	0.140	1.417	0.198
C	3	150	84.8	101.7	173.7	0.144	1.482	0.213
C	4	150	65.1	98.9	151.2	0.149	1.435	0.213
C	1	170	77.0	100.4	162.7	0.172	1.428	0.245
C	2	170	75.6	94.7	156.1	0.176	1.342	0.237
C	3	170	64.6	100.5	148.9	0.192	1.405	0.270
C	4	170	84.3	96.7	165.2	0.195	1.348	0.263
C	1	190	64.9	98.4	146.0	0.213	1.352	0.288
C	2	190	65.5	94.5	143.8	0.207	1.305	0.270
C	3	190	65.6	101.9	150.2	0.204	1.410	0.288
C	4	190	65.2	90.8	140.3	0.209	1.252	0.262

*cc is cm^3

Note: The shaded numbers were not included in the calibration due to "problems" with the corresponding soil samples, e.g., incomplete sample.

Table 4. Neutron probe field calibration—Soil data for the ‘wet’ set

Access Tube	Sample No.	Depth (cm)	Tare (g)	Fresh Weight Net (g)	O.D. Weight w/tare (g)	Water Content (g/g)	Bulk Density (g/cc*)	Water Content (cc/cc)
D	1	10	70.4	94.2	150.0	0.183	1.327	0.243
D	2	10	64.7	87.7	139.1	0.179	1.240	0.222
D	3	10	65.1	116.8	163.4	0.188	1.638	0.308
D	4	10	64.9	111.2	159.0	0.182	1.568	0.285
D	1	30	64.3	110.4	157.2	0.188	1.548	0.292
D	2	30	65.1	114.1	161.0	0.190	1.598	0.303
D	3	30	85.4	98.5	169.3	0.174	1.398	0.243
D	4	30	64.6	104.1	152.2	0.188	1.460	0.275
D	1	50	65.5	98.6	151.2	0.151	1.428	0.215
D	2	50	64.1	98.6	150.5	0.141	1.440	0.203
D	3	50	65.5	94.9	148.6	0.142	1.385	0.197
D	4	50	65.1	91.6	144.7	0.151	1.327	0.200
D	1	70	65.6	94.0	148.9	0.128	1.388	0.178
D	2	70	74.0	95.3	157.8	0.137	1.397	0.192
D	3	70	65.3	91.6	146.0	0.135	1.345	0.182
D	4	70	65.2	92.6	146.9	0.133	1.362	0.182
D	1	90	65.6	94.2	148.4	0.138	1.380	0.190
D	2	90	64.6	95.7	148.8	0.137	1.403	0.192
D	3	90	73.0	94.4	156.1	0.136	1.385	0.188
D	4	90	84.6	95.5	168.6	0.137	1.400	0.192
D	1	110	64.4	97.5	150.2	0.136	1.430	0.195
D	2	110	68.0	95.7	152.5	0.133	1.408	0.187
D	3	110	64.7	96.8	147.5	0.169	1.380	0.233
D	4	110	74.4	77.7	141.7	0.155	1.122	0.173
D	1	130	64.2	101.1	152.1	0.150	1.465	0.220
D	2	130	65.4	100.3	149.5	0.193	1.402	0.270
D	3	130	64.5	101.2	152.3	0.153	1.463	0.223
D	4	130	75.6	80.2	144.9	0.157	1.155	0.182
D	1	150	72.0	98.0	156.3	0.163	1.405	0.228
D	2	150	73.6	70.5	135.2	0.144	1.027	0.148
D	3	150	71.4	94.4	152.5	0.164	1.352	0.222
D	4	150	65.2	97.9	149.3	0.164	1.402	0.230
D	1	170	64.5	102.2	151.1	0.180	1.443	0.260
D	2	170	65.3	98.3	148.1	0.187	1.380	0.258
D	3	170	73.8	90.7	150.5	0.183	1.278	0.233
D	4	170	84.2	92.3	162.4	0.180	1.303	0.235
D	1	190	64.4	86.7	138.1	0.176	1.228	0.217
D	2	190	84.3	86.8	158.0	0.178	1.228	0.218
D	3	190	65.1	101.1	149.2	0.202	1.402	0.283
D	4	190	77.0	100.9	160.9	0.203	1.398	0.283
E	1	10	74.5	91.6	151.6	0.188	1.285	0.242
E	2	10	77.4	95.5	157.9	0.186	1.342	0.250

Table 4 (Continued)

Access Tube	Sample No.	Depth (cm)	Tare (g)	Fresh Weight Net (g)	O.D. Weight w/tare (g)	Water Content (g/g)	Bulk Density (g/cc)	Water Content (cc/cc)
E	3	10	73.7	114.3	170.0	0.187	1.605	0.300
E	4	10	70.5	107.7	160.5	0.197	1.500	0.295
E	1	30	65.5	110.0	158.6	0.182	1.552	0.282
E	2	30	64.7	107.7	155.9	0.181	1.520	0.275
E	3	30	72.9	106.8	164.2	0.170	1.522	0.258
E	4	30	76.3	108.9	169.0	0.175	1.545	0.270
E	1	50	65.8	98.9	152.4	0.142	1.443	0.205
E	2	50	64.9	99.5	151.8	0.145	1.448	0.210
E	3	50	75.6	99.3	163.5	0.130	1.465	0.190
E	4	50	65.2	93.3	146.0	0.155	1.347	0.208
E	1	70	65.4	92.6	146.6	0.140	1.353	0.190
E	2	70	65.6	95.8	149.8	0.138	1.403	0.193
E	3	70	65.0	64.4	121.6	0.138	0.943	0.130
E	4	70	64.6	100.9	153.5	0.135	1.482	0.200
E	1	90	85.4	94.8	169.0	0.134	1.393	0.187
E	2	90	64.8	97.6	150.9	0.134	1.435	0.192
E	3	90	64.9	96.7	149.2	0.147	1.405	0.207
E	4	90	64.9	98.8	152.6	0.127	1.462	0.185
E	1	110	65.2	85.0	137.7	0.172	1.208	0.208
E	2	110	65.4	99.9	150.6	0.173	1.420	0.245
E	3	110	64.1	98.4	148.9	0.160	1.413	0.227
E	4	110	65.0	96.3	151.1	0.118	1.435	0.170
E	1	130	65.7	100.2	152.0	0.161	1.438	0.232
E	2	130	84.8	82.0	154.7	0.173	1.165	0.202
E	3	130	64.7	101.6	153.0	0.151	1.472	0.222
E	4	130	65.5	102.1	153.7	0.158	1.470	0.232
E	1	150	64.2	94.7	145.6	0.163	1.357	0.222
E	2	150	64.9	105.6	155.4	0.167	1.508	0.252
E	3	150	64.0	100.8	150.4	0.167	1.440	0.240
E	4	150	65.8	101.2	153.2	0.158	1.457	0.230
E	1	170	64.6	93.4	143.0	0.191	1.307	0.250
E	2	170	68.7	98.7	151.9	0.186	1.387	0.258
E	3	170	84.8	100.3	168.5	0.198	1.395	0.277
E	4	170	65.4	100.2	149.3	0.194	1.398	0.272
E	1	190	84.1	101.9	169.3	0.196	1.420	0.278
E	2	190	64.6	99.9	147.7	0.202	1.385	0.280
E	3	190	65.7	101.0	149.9	0.200	1.403	0.280
E	4	190	65.0	102.9	150.5	0.204	1.425	0.290
F	1	10	65.7	93.3	144.3	0.187	1.310	0.245
F	2	10	65.1	93.0	142.8	0.197	1.295	0.255
F	3	10	65.2	110.5	158.2	0.188	1.550	0.292
F	4	10	65.1	111.3	158.4	0.193	1.555	0.300
F	1	30	65.8	110.1	159.0	0.181	1.553	0.282

Table 4 (Continued)

Access Tube	Sample No.	Depth (cm)	Tare (g)	Fresh Weight Net (g)	O.D. Weight w/tare (g)	Water Content (g/g)	Bulk Density (g/cc)	Water Content (cc/cc)
F	2	30	80.5	108.7	172.5	0.182	1.533	0.278
F	3	30	64.9	109.2	158.1	0.172	1.553	0.267
F	4	30	65.5	110.8	159.8	0.175	1.572	0.275
F	1	50	65.1	99.1	151.6	0.146	1.442	0.210
F	2	50	65.4	96.3	148.6	0.157	1.387	0.218
F	3	50	65.8	96.2	149.8	0.145	1.400	0.203
F	4	50	65.6	93.0	146.5	0.150	1.348	0.202
F	1	70	65.7	98.8	153.3	0.128	1.460	0.187
F	2	70	65.4	94.2	148.3	0.136	1.382	0.188
F	3	70	64.6	83.2	138.2	0.130	1.227	0.160
F	4	70	65.2	97.3	151.3	0.130	1.435	0.187
F	1	90	65.1	99.4	153.8	0.121	1.478	0.178
F	2	90	65.4	93.5	148.4	0.127	1.383	0.175
F	3	90	64.2	99.1	151.9	0.130	1.462	0.190
F	4	90	64.6	103.1	155.6	0.133	1.517	0.202
F	1	110	65.6	90.6	143.6	0.162	1.300	0.210
F	2	110	64.8	94.4	145.6	0.168	1.347	0.227
F	3	110	64.9	101.2	151.8	0.165	1.448	0.238
F	4	110	65.0	81.1	134.4	0.169	1.157	0.195
F	1	130	65.5	95.8	146.7	0.180	1.353	0.243
F	2	130	64.8	69.5	123.3	0.188	0.975	0.183
F	3	130	64.4	87.0	139.9	0.152	1.258	0.192
F	4	130	65.3	102.5	154.2	0.153	1.482	0.227
F	1	150	65.3	94.9	148.2	0.145	1.382	0.200
F	2	150	64.8	107.6	157.8	0.157	1.550	0.243
F	3	150	64.9	102.5	153.9	0.152	1.483	0.225
F	4	150	69.8	98.8	156.7	0.137	1.448	0.198
F	1	170	64.9	100.0	150.6	0.167	1.428	0.238
F	2	170	65.3	105.5	156.8	0.153	1.525	0.233
F	3	170	80.9	93.5	160.9	0.169	1.333	0.225
F	4	170	64.6	105.9	155.6	0.164	1.517	0.248
F	1	190	65.8	83.7	137.2	0.172	1.190	0.205
F	2	190	64.9	84.3	136.6	0.176	1.195	0.210
F	3	190	64.9	101.4	149.9	0.193	1.417	0.273
F	4	190	65.1	102.1	150.9	0.190	1.430	0.272

*cc is cm^3

Note: The shaded numbers were not included in the calibration due to "problems" with the corresponding soil samples e.g., incomplete sample.

Table 5. Neutron probe field calibration readings/counts

4-minute standard counts						
Tubes A&B	6603	6606	NA	Tube D	6603	6601
Tube C	6633	6552	6561	Tube E	6635	6564
				Tube F	6652	6624
Access Tube	**Depth (cm)**	**1-min Count[1]**	**Count Ratio[2]**	**Access Tube**	**1-min Count[1]**	**Count Ratio[2]**
A	10	7121	1.078	D	8567	1.298
A	30	8743	1.324	D	9508	1.440
A	50	6971	1.055	D	7780	1.178
A	70	6057	0.917	D	7219	1.093
A	90	6770	1.025	D	7544	1.143
A	110	7076	1.071	D	8250	1.250
A	130	7328	1.109	D	8208	1.243
A	150	7707	1.167	D	8427	1.276
A	170	8215	1.244	D	8808	1.334
A	190	8982	1.360	D	9376	1.420
B	10	6550	0.992	E	8650	1.311
B	30	8397	1.271	E	9283	1.407
B	50	7080	1.072	E	7736	1.172
B	70	6033	0.913	E	7287	1.104
B	90	6898	1.044	E	7643	1.158
B	110	7476	1.132	E	8020	1.215
B	130	7317	1.108	E	8462	1.282
B	150	7692	1.165	E	8558	1.297
B	170	8661	1.311	E	9001	1.364
B	190	9205	1.394	E	9261	1.403
C	10	6555	0.996	F	8735	1.316
C	30	8155	1.239	F	9390	1.415
C	50	6822	1.036	F	7769	1.170
C	70	6127	0.931	F	7057	1.063
C	90	7079	1.076	F	7393	1.114
C	110	7422	1.128	F	8237	1.241
C	130	7347	1.116	F	8477	1.277
C	150	7701	1.170	F	8173	1.231
C	170	8451	1.284	F	8295	1.250
C	190	9019	1.370	F	9126	1.375

[1]Average of two readings

[2]One-minute count/Average standard count

Table 6. Average soil moisture and count ratios used to calibrate the neutron probe CPN 503DR at the Arkansas Valley Research Center

Access Tube	Depth (cm)	Water Content (g/g)	Bulk density (g/cc*)	Water content (cc/cc)	Count Ratio
A	10	0.140	1.447	0.203	1.078
A	30	0.153	1.547	0.236	1.324
A	50	0.122	1.519	0.185	1.055
A	70	0.112	1.398	0.157	0.917
A	90	0.131	1.380	0.181	1.025
A	110	0.144	1.387	0.200	1.071
A	130	0.138	1.458	0.201	1.109
A	150	0.140	1.463	0.204	1.167
A	170	0.173	1.360	0.235	1.244
A	190	0.195	1.390	0.271	1.360
B	10	0.129	1.387	0.185	0.992
B	30	0.148	1.567	0.232	1.271
B	50	0.133	1.522	0.202	1.072
B	70	0.107	1.379	0.147	0.913
B	90	0.136	1.362	0.186	1.044
B	110	0.157	1.403	0.221	1.132
B	130	0.137	1.433	0.196	1.108
B	150	0.136	1.475	0.200	1.165
B	170	0.173	1.403	0.243	1.311
B	190	0.206	1.398	0.288	1.394
C	10	0.123	1.493	0.190	0.996
C	30	0.146	1.511	0.221	1.239
C	50	0.124	1.496	0.186	1.036
C	70	0.115	1.404	0.162	0.931
C	90	0.139	1.390	0.193	1.076
C	110	0.156	1.382	0.215	1.128
C	130	0.143	1.373	0.197	1.116
C	150	0.141	1.450	0.204	1.170
C	170	0.184	1.381	0.254	1.284
C	190	0.208	1.356	0.283	1.370
D	10	0.183	1.443	0.265	1.298
D	30	0.185	1.501	0.278	1.440
D	50	0.146	1.395	0.204	1.178
D	70	0.134	1.373	0.183	1.093
D	90	0.137	1.392	0.190	1.143
D	110	0.148	1.406	0.208	1.250
D	130	0.153	1.371	0.224	1.243
D	150	0.164	1.386	0.227	1.276
D	170	0.183	1.351	0.247	1.334
D	190	0.202	1.400	0.283	1.420

Table 6 (Continued)

Access Tube	Depth (cm)	Water Content (g/g)	Bulk density (g/cc)	Water content (cc/cc)	Count Ratio
A	10	0.140	1.447	0.203	1.078
E	10	0.189	1.433	0.272	1.311
E	30	0.177	1.535	0.271	1.407
E	50	0.147	1.413	0.208	1.172
E	70	0.138	1.413	0.195	1.104
E	90	0.135	1.424	0.193	1.158
E	110	0.168	1.347	0.227	1.215
E	130	0.156	1.460	0.228	1.282
E	150	0.164	1.440	0.236	1.297
E	170	0.193	1.372	0.264	1.364
E	190	0.200	1.408	0.282	1.403
F	10	0.191	1.428	0.273	1.316
F	30	0.177	1.553	0.275	1.415
F	50	0.149	1.394	0.208	1.170
F	70	0.131	1.426	0.187	1.063
F	90	0.128	1.460	0.186	1.114
F	110	0.166	1.365	0.226	1.241
F	130	0.162	1.364	0.221	1.277
F	150	0.148	1.466	0.217	1.231
F	170	0.163	1.451	0.236	1.250
F	190	0.186	1.423	0.265	1.375

*cc is cm^3