ARS Technical Bulletin NWRC-2000-7

August 11, 2000

LONG-TERM SOIL MICROCLIMATE DATABASE: REYNOLDS CREEK EXPERIMENTAL WATERSHED, IDAHO, USA

MARK S. SEYFRIED
GERALD N. FLERCHINGER
CLATYON L. HANSON
MARK D. MURDOCK
STEVEN S. VAN VACTOR

USDA-Agricultural Research Service
Northwest Watershed Research Center
800 Park Blvd, Suite 105
Boise, ID 83712-7716

LONG-TERM SOIL MICROCLIMATE DATABASE: REYNOLDS CREEK EXPOERIMENTAL WATERSHED, IDAHO, USA

MARK S. SEYFRIED
GERALD.N. FLERCHINGER
CLATYON.L. HANSON
MARK D. MURDOCK
STEVEN S. VAN VACTOR

USDA-ARS Northwest Watershed Research Center, Boise, ID 83712-7716
208/422-0700, mseyfrie@nwrc.ars.usda.gov

ABSTRACT

We describe long term data collected at the Reynolds Creek Experimental Watershed (RCEW) related to below-ground fluxes of energy and water. Three kinds of data are described: (i) evapotranspiration (ET) as measured by lysimeter, (ii) soil water content as measured by neutron probe, and (iii) soil temperature. The length of record ranges from 15 years for the lysimeter and soil temperature data to 25 years for the neutron probe data. These data were collected at locations representing different climates and soils within the RCEW. Spatial variability of water balance within the watershed and well as temporal variability at specific sites is illustrated. High correlation between neutron probe and lysimeter results are the basis for assessing the accuracy of neutron probe-measured changes in soil-water content. All data are available to the public via the internet.

1. INTRODUCTION

Quantifying fluxes of water and energy between the soil and atmosphere requires an understanding of the soil microclimate. Microbial processes that result in the mineralization of essential plant nutrients and consequent release of carbon dioxide to the atmosphere are controlled by soil temperature and soil water content (Sommers et al., 1981). Seed germination and plant root growth, both of which affect water, energy and gas fluxes, are also dependent on the soil microclimate. These processes constitute direct and indirect feedbacks to atmospheric forcings which are increasingly considered critical for improving global circulation models. In this chapter we describe long term data from different sites in the RCEW which is, to our knowledge, unprecedented in terms of temporal scope and climatic diversity.

Three soil microclimate data sets are included: (i) lysimeter, (ii) soil water content, (iii) and soil temperature. These data were generally collected at or near the three primary RCEW climate stations (see the spatial data report for locations) and therefore compliment that data. All measurement sites have been located with GPS and positions are available in UTM coordinates. The sites are dispersed along the length of the RCEW (Figure 1). With the exception of some soil water content data, slopes are within 2 or 3 degrees of horizontal, so that the data are essentially aspect neutral and reflect conditions at different elevations within the RCEW. In contrast to the climate and runoff data, these data are not serially complete and we have made no attempt (with a few noted exceptions) to estimate values for unrecorded times. The subsections describing the lysimeter and soil water data are considerably longer than that describing soil temperature because the interpretation of those data is less straightforward.

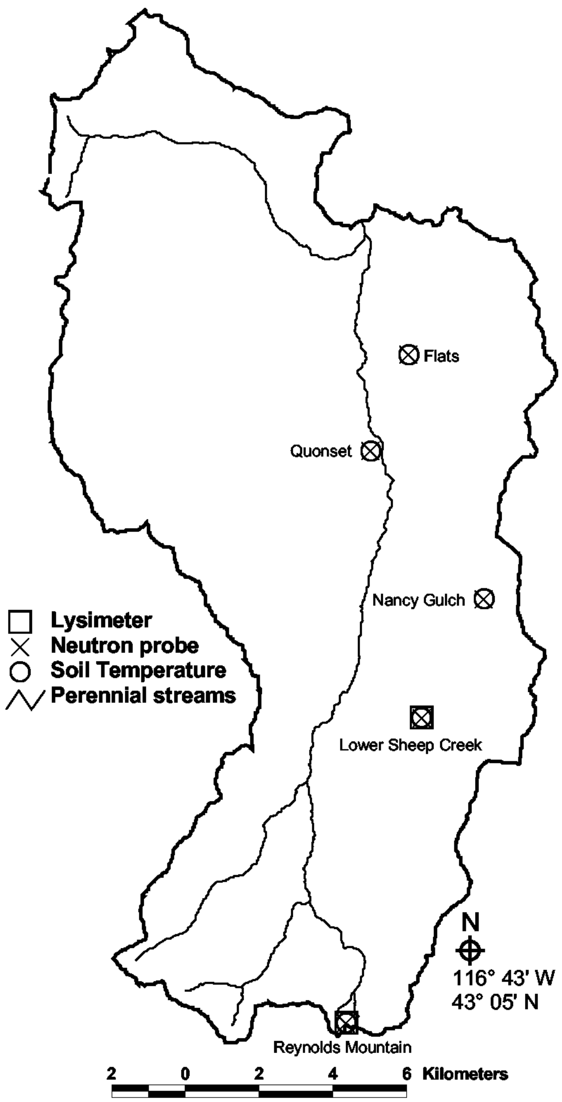

Figure 1. Location of soil micoclimate data collection sites. The neutron probe sites include 2 to 5 individual access tubes in relatively close proximity.

2. LYSIMTERS

2.1 Overview

Soil lysimeters have been used for many years to measure evapotranspiration (ET) and other related processes in a relatively controlled field environment (e.g., Howell et al., 1991). Calculation of ET for a specified time period is based on the following equation:

$$ET = P - (V_L + V_R + \Delta V_S)/A \qquad (1)$$

where P is precipitation (mm), V_L is the volume drainage loss (mm^3), V_R is volume of net surface runon/runoff (mm^3), ΔV_S (mm^3) is the change in the volume of soil water in the lysimeter during the specified time period and A (mm^2) is the area of the lysimeter (Tanner, 1967). If the lysimeter is well sealed and overland flow prevented, V_L and V_R are 0. Therefore, ET can be calculated from measured values of P, A, and ΔV_S. Enclosed lysimeters of the type described in this report measure weight-induced pressure changes for a known constant soil volume. Measured changes are attributed to changes in soil water and converted to a volumetric basis using the density of water. These are reported as the lysimeter water content change per unit area ($\Delta V_S/A$ or ΔW, in mm of water) as are ET and P. In this report we describe the ΔW data. Calculation of ET requires precipitation data supplied in a companion report (Hanson et al., 2000).

2.2 Lysimeter Description

Two pairs of soil lysimeters were installed in the RCEW in 1967, one pair at the Lower Sheep Creek climate station (designated the "east" and "west" lysimeters), separated, center to center, by 3.6 m and the other at the Reynolds Mountain climate station (designated "north" and "south"), separated by 4.7 m (see Table 1 for UTM coordinates and elevations). These lysimeters are hydraulic weighing lysimeters (e.g., Tanner, 1967; Kruse and Neale, 1991) in which an inner cylindrical tank containing soil is set within a slightly larger outer cylinder. The inner cylinder rests on a coil of 0.05 m diameter butyl tubing filled with liquid (different low freezing point liquids were used). The inner cylinder was 1.22 m deep and 1.47 m in diameter. The butyl tubing was hydraulically connected underground to a pressure transducer or manometer. Changes in pressure were related to changes in weight of the lysimeter via calibration. Assuming negligible changes in soil and plant biomass (reasonable in this case), ΔW could be calculated directly.

Table 1. Location of lysimeters.

	UTM Coordinates (m)					
	GPS Measured			DEM Pixel		
	Easting	Northing	Elevation	Easting	Northing	Elevation
LSC* East	521741	4776182	1656	521730	4776170	1656
LSC West	521738	4776184	1656	521730	4776170	1656
RM† North	519707	4767900	2098	519720	4767890	2097
RM South	519710	4767896	2098	519720	4767890	2097

*Lower Sheep Creek
† Reynolds Mountain

The soil in each lysimeter was extracted from near the lysimeter sites. A soil core was taken by repeatedly excavating a soil cylinder of slightly larger diameter than the lysimeter and forcing the lysimeter sleeve over the soil to the depth of the sleeve (1.22 m). A metal plate was then forced across the cylinder bottom and welded to it in place. The inner cylinder, thus filled with soil, was then transported to the previously excavated outer cylinder via crane and set on the butyl tubing. A neutron access tube was installed in the center of each lysimeter (see next section for details) to monitor soil water content changes with depth, and two 1.2 m ceramic suction "candles" were placed at the bottom of the lysimeters through a separate entrance.

This operation resulted in an undisturbed soil monolith with extant vegetation in place (e.g., Schneider and Howell, 1991). This is critical for two reasons, (i) growing native vegetation under natural conditions is problematic in this environment and plant development slow, and (ii) the soil horizonation, particularly the argillic and calcic horizons which are both strongly embedded in coarse fragments, would be essentially impossible to reproduce artificially.

The vegetation at the Lower Sheep Creek site is dominated by low sagebrush (see Seyfried et al., 2000, for scientific names) which grows to a height of about 0.3 m and is accompanied by perennial bunchgrasses and forbs (see Seyfried et al., 2000 for a description of vegetation at the RCEW). Grasses include bluebunch wheatgrass and Sandberg bluegrass. Lupine is a common forb. The percent vegetative cover is typically around 40% and leaf area index (LAI) ranges from around 0.2 to 0.9. Individual shrubs are typically separated by about one meter. The two lysimeters each contained a mature shrub along with the naturally associated plants. The LAI for each of the lysimeters was monitored several times each year using the point quadrature method (Clark and Seyfried, 2000). Maximum LAI values tend to be a little higher than those for most of the area. The two lysimeters at Lower Sheep Creek have almost identical LAIs and timing of maximum and minimum annual LAI (Table 2).

Table 2. Date and Value of Average Maximum and Minimum Leaf Area Index (LAI).

Lysimeter	Maximum Date	Maximum LAI	Minimum Date	Minimum LAI
Reynolds Mt. North	30 June	2.04	1 Oct.	0.597
Reynolds Mt. South	3 July	1.78	4 Oct.	0.441
Lower Sheep Creek East	23 May	1.57	20 Sept.	0.296
Lower Sheep Creek West	22 May	1.50	21 Sept.	0.352

The vegetation near the Reynolds Mountain site is dominated by mountain sagebrush, which is taller (height is about 0.6-0.9 m) and usually grows more densely than low sagebrush. Associated plants include mountain snowberry, Idaho fescue and yarrow. As at Lower Sheep Creek, the timing and magnitude of LAI changes are practically identical at the two lysimeters (Table 2). These two lysimeters also contained a single shrub, which tends to result in slightly higher LAI's than typical for the area. Note that the date of maximum LAI at Reynolds Mountain occurs about 40 days after that at Lower Sheep Creek. This reflects the deeper, later lying snow pack, cooler air temperatures and greater precipitation at Reynolds Mountain (see Hanson, 2000; Hanson et al.., 2000;, Marks et al., 2000).

2.3 Data Collection

Although the lysimeters became operational in 1968, there were a number of problems associated with the measurement instrumentation and consistent digital data is not available until 1976 at Lower Sheep Creek (Lower Sheep Creek East and West) and 1979 at Reynolds Mountain (Reynolds Mountain North and South). Data collected through 1984 are daily values. Each year data was recorded from spring until fall, starting with $\Delta W \approx 0$ mm each spring. Thus, the last ΔW reading each year represents the net ΔW for that time interval. Missing data were treated as follows: (i) when the record was sparse or inconsistent for extended times, a single, monthly ΔW value was recorded near the end of each month (denoted "M"), (ii) where there were small (one or two day) data gaps, intermediate values were estimated (denoted "E") by interpolation considering weather inputs, and (iii) where data was interrupted for longer, irregular times (i.e., several days) the pooled ΔW value at the end of that time is recorded (denoted "P").

During 1984 digital data logging systems were installed that recorded hourly values all year. Hourly data is reported from 1/1/1985 until lightening strikes in 1992 interrupted data collection and the systems were discontinued. Note that, unlike some other data we report, the lysimeter data is reported on a calendar year basis. No pooled, estimated or monthly data are included in the hourly data set. Evapotranspiration can be calculated using Eq.1 and precipitation measured at the near-by precipitation gauge.

2.4 Calibration

All four lysimeters were calibrated each fall. The calibration procedure was to place known weights on the lysimeters and then record the resultant pressure changes. The weights used were as follows: 19.9 kg for supportive blocks placed on the lysimeter, 43.4 kg for the tank which contained the weights, and then 24, 22.7 kg sacks of rock added in 4 sack increments. The weight of each sack corresponds to about a 13 mm addition of water so that weight increments were equivalent to about 52 mm and the total range was about 360 mm of water. Measurements were made both as weight was added and removed.

The coefficient of determination (r^2) between measured pressure and added weight for each individual lysimeter was very high ($\geq$0.99). Since difference alone is of interest, and the relationship was linear, the calibration required to convert measured pressure changes to ΔW is simply the slope of the pressure-weight (converted to water volume) relationship. The measured calibration constants (slopes) were significantly different among individual lysimeters. There was no significant ($\alpha = 0.05$) difference between calibration constants measured while adding or subtracting weight for the years investigated, indicating that the butyl tubing was appropriately filled (Kruse and Neale, 1991). In addition, there was little change in calibration constant over the years, and no apparent trend. We therefore represented each lysimeter with a single calibration constant for the period of record.

The 95% confidence interval about the mean calibration constant was 0.796 Pa/mm H_2O at the Reynolds Mountain South (RMS) lysimeter and 0.8895 Pa/mm H_20 at Lower Sheep Creek west (LSCW) lysimeter. For perspective, a change in calibration constant to the extreme of the 95% confidence interval for a year in which $\Delta W = 200$ mm (which is common) results in a deviation of $\pm$ 5 mm at the RMS lysimeter and $\pm$ 8 mm at the LSCW lysimeter. Thus, year to year variation in calibration should have little effect on lysimeter measurements.

Comparison of the paired lysimeters, indicates that, although the pairs generally agree in the qualitative sense of exhibiting the same trends, there often are considerable differences between them (Figure 2a,b). Note that in both Figure 2a and 2b the paired lysimeters agreed closely at the beginning and end of the year but differed by as much as 70 or 80 mm during the year. Thus, either at least two of the lysimeters (one at each location) did not represent soil water dynamics well or those dynamics were quite different among the different individuals for each pair. The second explanation seems unlikely given that the lysimeters are in practically the same location with practically the same soil and vegetation.

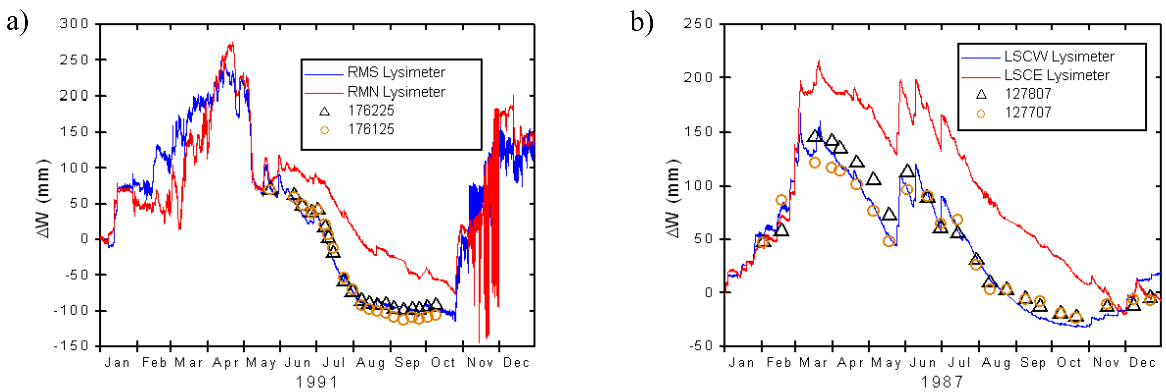

Figure 2. Changes in the lysimeter water content (ΔW) compared with that calculated from neutron probe measurements at: a) the north (RMN) and south (RMS) lysimeters at Reynolds Mountain during 1991 and b) at the east (LSCE) and west (LSCW) lysimters at Lower Sheep Creek for 1987. The six digit numbers refer to neutron access tubes located in the lysimeters.

We used complimentary soil water content data collected in the lysimeters with neutron probes to determine which, if either of the lysimeter pair members functioned properly. (Neutron probe data is described in detail in the next section of this report). We found that ΔW calculated from neutron probe data for each pair was essentially identical, indicating that the soil water dynamics were similar within each lysimeter pair as expected (Figure 3 a,b). Furthermore, we found that the neutron probe-calculated ΔW generally agreed with that calculated from at least one of the two lysimeters at each site (Figure 2a, b). Using the 128 neutron probe measurements taken between 1980 and 1992 at the RMS lysimeter, the linear correlation between neutron probe and lysimeter calculated ΔW was strong (r^2 = 0.98) with very little bias (slope = 1.03, Y intercept = 0.23) (Figure 4 a,b). Similarly, the correlation between ΔW calculated from the 218 neutron probe readings made between 1976 and 1992 (excluding 1977 and 1978) and the lysimeter measurements at the LSCW lysimeter was also linear (r^2 = 0.92) and only slightly biased with a slope of 1.04 and Y-intercept of 0.00298 (Figure 4 a, b).

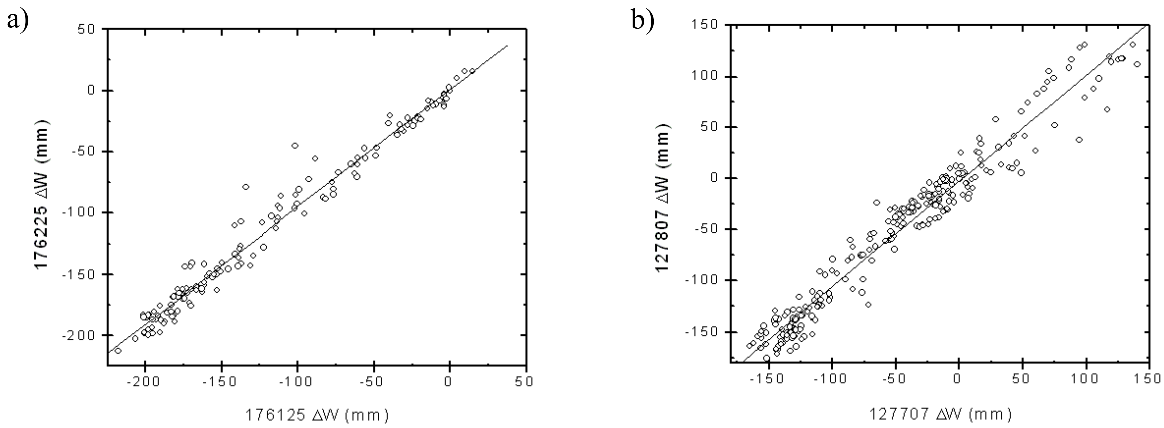

Figure 3. Comparison of total water content calculated from neutron probe measurements in matching lysimeters at a) Reynolds Mountain north (access tube 176125 and south (access tube 176225) and b) Lower Sheep Creek east (access tube 127707) and west (access tube 127807).

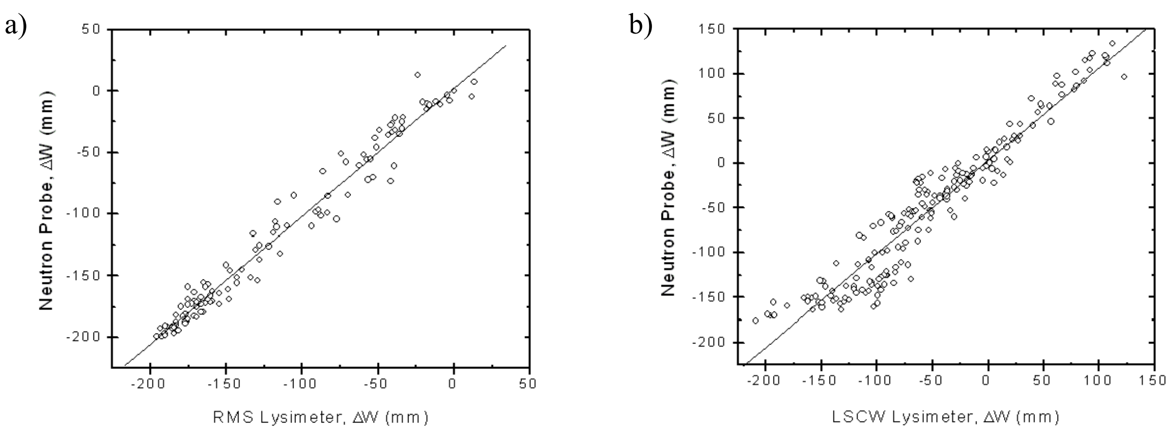

Figure 4. Comparison of neutron probe calculated and lysimeter measured ΔW over the measurement period (see Table 3) for the: a) Reynolds Mountain south (RMS) lysimeter and b) the Lower Sheep Creek west (LSCW) lysimeter. Neutron probe data are the average of the two access tubes at each site.

Based on these observations, our criteria for including lysimeter data in this data report were that there be good agreement between the neutron probe and lysimeter measured ΔW over the growing season. This resulted in basically two lysimeters reporting, Reynolds Mountain south for 12 years and LSCW for 15 years (Table 3). We have no good explanation for the fact that, while the calibration statistics for the four lysimeters were similar, two of them did not seem to function. Apparently there was some resistance in the system that was overcome by the relatively large weight increments used for calibration but effectively "caught" with small weight increments.

Table 3. Lysimeter data availability.

Year	LSC* East	LSC West	RM* North	RM South	Notes
1976		X			LSC East seemed to “stick”
1977					Very poor neutron probe correlation with both
1978	X	X			LSC East is monthly
1979	X	X			LSC East is monthly
1980		X	X	X	Starts July 5 for RM
1981	X	X		X	
1982	X	X		X	LSC East is good until 9/1/82
1983		X		X	
1984		X		X	
1985		X		X	
1986		X		X	LSC West starts after June 1, tubing replaced
1987		X		X	
1988		X		X	
1989		X		X	
1990		X		X	
1991		X		X	

* LSC refers to Lower Sheep Creek and RM to Reynolds Mountain

2.5 Other Considerations

The lysimeter data are difficult to interpret during times when there was significant snow cover. Data obtained during those times tends to be more variable than other times. What is more perplexing is the pronounced apparent decline in ΔW at the time of snowmelt that is obvious during snowmelt almost every year at Reynolds Mountain (e.g., Figure 2a, 5). Since neutron probe data were not collected during periods of deep snow cover, there is no check on the soil-water dynamics during those times.

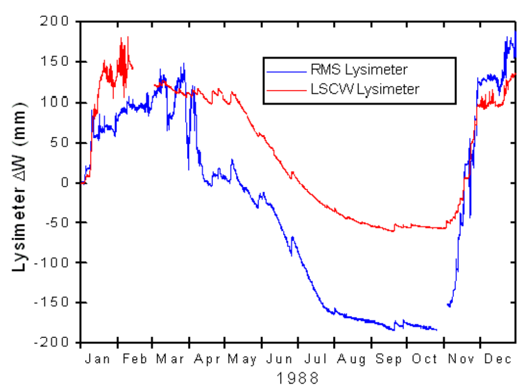

Figure 5. Comparison of ΔW dynamics at the south Reynolds Mountain lysimeter (RMS) and the west Lower Sheep Creek lysimeter (LSCW) during 1988.

Ceramic drainage "candles" were installed in all the lysimeters for drainage. The timing and amount of drainage are not known except that drainage was performed most years in the spring at both sites. Contrary to expectation, no water was collected from the Reynolds Mountain lysimeters ans some was collected from the Lower Sheep Creek lysimeters. It seems reasonable to assume that the soil in the lysimeters had artificially high water contents at times. This effect would be more evident at Reynolds Mountain where there is considerably more precipitation than at Lower Sheep Creek, where the wetting front often fails to penetrate much more than a meter.

2.6 Sample Data

Typical hourly data, collected at the RMS and LSCW lysimeters in 1988 are presented in Figure 5. The relatively noisy data early in the year at both sites is indicative of snow cover, which was gone by 1 March at LSCW and mid April at RMS. The sharp decline in weight at the time of snowmelt observed at RMS is also common. Net water loss occurred more gradually at LSCW. It has lost about 1/3 of it's total water by 1 June, and about 2/3 but 1 July, while at RMS the net loss was less than 1/10 on 1 June and was still less than ½ on 1 July. Maximum ET rates were considerably greater at RMS, where maximum LAI, available soil water and atmospheric demand are in closer synchrony than at LSCW. During late June to the end of July, when there was practically no rainfall, the LSCW lysimeter lost 40 mm of water (about 1.3 mm/day) and the RMS lysimeter lost 80 mm of water (2.7 mm/day). Essentially all available water was transpired from both lysimeters by the end of summer, as is expected in this climate.

3. SOIL WATER CONTENT WITH NEUTRON PROBE

3.1 Overview

Soil water has been part of the data collection efforts at the RCEW nearly since the project's inception. Several projects have been undertaken that examine soil water dynamics in the RCEW (e.g., Rawls et al., 1973; Stephenson and Zuzel, 1981; Seyfried, 1998). Since 1970 there has been a sustained effort to monitor soil water content at specific locations in conjunction with the meteorological and hydrological monitoring networks. In this section we describe long term soil water content measurements made periodically at different depths using neutron probe.

3.2 Instrumentation

The neutron probe was first developed in the 1950's (Gardner and Kirkham, 1952) and has been a well accepted method for measuring soil water content for many years (Chanasyk and Naeth, 1996). As with all instruments, there are limitations to the neutron probe that are both inherent in its mode of operation and dependent on the methodology and circumstances of use for a particular study. In this section we provide information to allow potential users of this data to evaluate the latter as they apply to the specific objectives of a given project. There are a variety of references that specifically address to the neutron method in principle (e.g., Greacen, 1981; Gardner, 1986).

Five different neutron probes were used over a 26 year period (Table 4). From 1970 to 1979, two probes manufactured by Troxler were used, these were replaced with two probes manufactured by Campbell Nuclear Pacific. A different Troxler instrument was used briefly near the end of the study. All the probes reported used Americium 241/Berylium as the radiation source. During most of the monitoring period, one probe was designated as the primary instrument and the other was used as a backup and for specific, individual studies.

Table 4. Description of neutron probes used during the measurement period.

Label*	Manufacturer	Strength (Gbq)	Years Used	Detector	Model #
492	Troxler	3.7	1970–1980	BF_3	1255
152	Troxler	3.7	1970–1979	BF_3	1255
606	CNP†	1.86	1979–1976	BF_3	503A
607	CNP	1.86	1979–1976	BF_3	503A
217	Troxler	0.37	199?–1996	^3He	3220

* Label applied at the NWRC
† Campbell Nuclear Pacific

3.3 Site Description

Data included in this report were collected from the following locations in the RCEW: Flats, Quonset, Nancy Gulch, Lower Sheep Creek, and Reynolds Mountain (see Seyfried et al., 2000, for a description of the sites and complimentary measurements at those sites). In all cases, the neutron access tubes are located within about 50 m of precipitation gauges. Lower Sheep Creek, the Quonset and Reynolds Mountain are also climate station sites. Weather information other than precipitation must be extrapolated from one of the climate stations for the Flats and Nancy Gulch sites. Individual access tubes are labeled with the nomenclature described in Seyfried et al. (2000). Locations of each access tube is also provided in UTM coordinates (Table 5).

Table 5. Site information for neutron probe data.

Site Name	Tube ID	Years of Record	Location (UTM)	Depth (m)	Visit/ year	Soil Description
Flats	057896	1973–1996	521491E 4785951N	1.22	22	S 81ID-073-003
Flats	057C96	1971–1996	521526E 4785956N	1.22	22	S 81ID-073-003
Flats	057H96	1986–1996	521386E 4786029N	0.91	20	S 81ID-073-004
Quonset	076059	1981–1996	520388E 4783423N	1.22*	19	Not Available
Quonset	076159	1987–1996	520372E 4783418N	0.91	19	S 81ID-073-004
Nancy Gulch	098697	1971–1996	523367E 4779370N	1.22	23	S 81ID-073-009
Nancy Gulch	098897	1973–1996	523347E 4779303N	1.22	23	S 81ID-073-009
Nancy Gulch	098F97	1973–1996	523448E 4779559N	0.61	21	S 81ID-073-009
Lower Sheep Creek	117079	1972–1996	521595E 4776403N	0.91	21	S 81ID-073-003
Lower Sheep Creek	117186	1973–1996	521599E 4776514N	2.74†	22	S 81ID-073-003
Lower Sheep Creek	117287	1973–1986 1990–1996	521759E 4776439N	2.13	21	S 81ID-073-004
Lower Sheep Creek	127707	1974–1993	521743E 4776182N	0.91	18	S 81ID-073-008
Lower Sheep Creek	127807	1970–1993	521741E 4776182N	0.91	18	S 81ID-073-008
Lower Sheep Creek	127907	1970–1996	521738E 4776184N	1.82	23	S 81ID-073-008
Reynolds Mountain	176006	1973–1996	520077E 4768151N	1.22	18	RM1
Reynolds Mountain	176025	1977–1996	519715E 4767899N	0.91	15	S 81ID-073-007
Reynolds Mountain	176125	1977–1993	519707E 4767900N	0.91	12	S 81ID-073-007
Reynolds Mountain	176225	1977–1993	519710E 4767896N	0.91	12	S 81ID-073-007

* 1981 and 1982 went to 0.91 m
† 1979, 80, 81 went only to 2.13 m

Detailed soil descriptions are available in the format described for the soil survey data for the access tube locations. Except where noted, these descriptions were made by NRCS personnel in 1982 with laboratory analysis performed at the laboratory in the Lincoln, Nebraska. At the Quonset, no pit descriptions were made and the two access tubes, although in close proximity, are in quite different soils. Tube 076159 was initiated in response to anomalously high water contents that were observed in tube 076059. We have provided a soil description from the nearby Flats area that is similar to the soil at tube 076159. The soil at tube 076059 has a higher clay content near the surface, although we have no specific pit description for that soil.

Access tube 176006 at Reynolds Mountain is separated somewhat from the climate station but very near precipitation gauge 176x07. Standing water has been noted in that access tube and the water table is relatively near the surface. The soil description included for that tube was taken from a detailed soil survey of the Reynolds Mountain subwatershed.

3.4 Data Collection

For a variety of reasons, the length of record and number of readings taken varies for different sites. The main data collection effort was initiated between 1970 and 1973 using 48 mm diameter aluminum access tubes installed to varying depths. The holes were excavated using a “Houston” rotary core drill using air pressure. This was essential for most sites due to the high rock contents common in RCEW soils. It was generally felt by early investigators that the sample volume probably changed slightly shortly after tube installation as the soil “settled” around the tubes.

Measurements at all tubes were made at a depths of 0.15 m and 0.305 m followed by readings at 0.305 m intervals to the bottom of the tube (Table 5). Except where noted, 30 s counting times were used for each reading. Readings were made at approximately biweekly intervals (Table 5) with about 20 readings per year. In general, the sites at lower elevations in the watershed were measured more frequently than those higher up due to snow cover and difficulty of access during the winter months. Extensions were placed on some of the tubes to allow monitoring during the winter. The data record for 1996 for all tubes is very sparse due to a combination of equipment failure and personnel changes.

Each of the four lysimeters described previously contained a neutron access tube, LSCE was 127707, LSCW was 127807, RMN was 176125 and RMS was 176225. The two tubes in the Reynolds Mountain lysimeters (176125 and 176225) were not monitored when there was significant snow cover because they were intended to track growing season soil water use. Readings at the Lower Sheep Creek lysimeters (127707 and 127807) were made almost as frequently as the others because snow covered the access tubes much less frequently.

3.5 Calibration

All probes were calibrated in standard source material (polyethylene) manufactured by Troxler (part numbers 7328-1,-2,-3) to simulate the following three water contents: 0.1096, 0.2121 and 0.3008 m^3m^{-3}. Each calibration consisted of five measurements made for each simulated water content along with 5 to 10 standard counts, which were usually of longer duration. The measured count ratios were fit to a simple linear regression equation of the form

$$\theta = mC_r + K \qquad (2)$$

where C_r is the count ratio (measured count/standard count), m is the slope of the θ/C_r relationship and K is the value of θ when C_r is 0 (Figure 6).

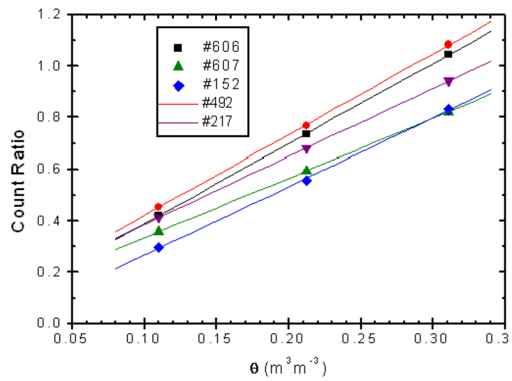

Figure 6. Calibrations from synthetic standards for each probe over the years the probes were in service (Table 6). The 95% confidence interval about each point is smaller than the point representing the data.

When all calibration data collected over the 9 to 15 year period over which an instrument was in use were examined, a very high degree of linearity was observed (Figure 6). The lowest coefficient of determination (r^2) was 0.995 for probe 152 (Table 6). Probes 606 and 607 had r^2 values of 0.999. In addition, no trend over time was discernable. Therefore, a single calibration equation was used for each instrument over the time reported. The *m* value was not significantly different ($\alpha = 0.01$) for probes 606 and 607 while for all other probes it was.

Table 6. Calibration statistics using the polyethylene standards.

Probe	m	K	r^2
152	43.12	-4.42	0.995
492	37.79	-4.56	0.996
606	32.24	-2.59	0.999
607	31.95	-3.48	0.999
217	37.54	-0.01	0.999

The measurements at each simulated water content also had a high degree of precision. The standard deviation of a given reading will increase with the square root of the number of counts (assuming a constant time interval), which can be evaluated for specific readings. For the calibration data, the 99% confidence interval for these instruments ranged from 0.008 m^3m^{-3} to 0.014 m^3m^{-3} for the highest water content and from 0.003 m^3m^{-3} to 0.009 m^3m^{-3} for the lowest. This high precision was also evident in field measurements. For example, for 208 measurements made between 2 September, 1986 and 14 November, 1995 at 098897, a wetting front was not apparent at depths either immediately above or below 0.91 m. The measured mean was 0.230 m^3m^{-3} with a 99% confidence interval of 0.0015 m^3m^{-3} (this is illustrated in a subsequent section, Figure 8).

In general, the calibration precision derived from the artificial standards was excellent and probably contributed little to the total variation from the "true" field soil water content. The problem with the calibration approach used is that, to the extent that the standards do not represent the field soil, bias was introduced. It can be assumed, for example, that the field soils in the RCEW (and in general) contain sources of hydrogen other than water (e.g., organic matter), that the bulk density of the field soil is different from that assumed for the standards, and that coarse fragments will alter the calibrations derived for the fine earth fraction. An additional source of bias must be considered in this report. Because the sampling volume of different neutron probes varies, there is a potential for significant instrument-induced effects. This would be most evident where there is strong soil horizonation or a sharp wetting front.

3.6 Probe Cross Calibration

Previous work by Reginato and Nakayama (1988) demonstrated that it is possible to cross calibrate probes of like manufacture using calibration standards. It is not clear how well that applies to probes of different manufacture because the sampling geometry may vary considerably.

On 15 March, 2, 4 and 10 May of 1979, cross calibration tests were performed using probe numbers 606, 607, 492 and 152 to determine the degree of correlation among different standard-calibrated probes in field soils. Seven access tubes were used, two at the Summit (not part of the long term data set), two at Nancy Gulch (098697 and 098897), two at the Flats (057096 and 57896), and one at Lower Sheep Creek (tube not known). On each date the different probes measured soil water at the same depths and approximately the same times.

In general, the correlation among instruments was high (Figure 7), with r^2 values ranging from 0.968 to 0.995. As expected, the highest correlations were between probes of like manufacture, so the correlation between probes 606 and 607 (r^2 = 0.995) and the correlation between probes 152 and 492 (r^2 = 0.981) was relatively high. In general, differences increased with water content such that estimates were within 0.01 m^3m^{-3} for low θ's (0.10 m^3m^3) and increased to 0.02 and 0.03 m^3m^{-3} when θ was greater than 0.30 m^3m^{-3}. These differences would not necessarily be the same at all sites and depths due to the effects of soil layering interacting with the different probe sampling geometries.

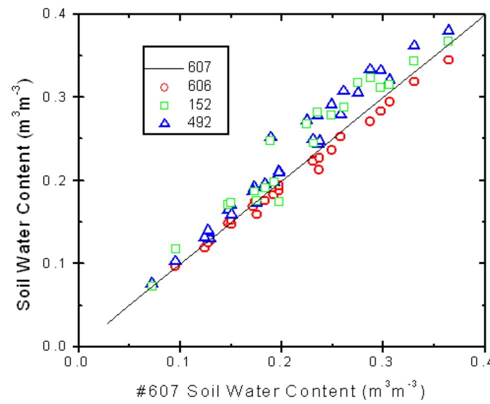

Figure 7. Cross calibration of four neutron probes at five different access tubes. Soil water content was calculated using standard-derived calibrations (Table 6). Results of each probe are plotted relative to probe #607, with the solid line representing perfect agreement with #607.

These data indicate that the calculated θ should have decreased when probe 607 replaced 492 in January of 1979 and that the decrease should have been greater as θ increased. Examination of data indicate that this did occur at some locations but the effect was not consistent. For example, for access tube 098897 (Figure 8) there appears to be a drop at the 0.61 m and possibly the 1.22 m depth but the effect is not clear at other depths at the site nor at some of the other sites. Therefore, we have not corrected for this "instrument effect" in the database.

3.7 Water Content Change Measurement Accuracy

Four of the long term access tubes were located in weighing lysimeters, 176125 and 176225 at Reynolds Mountain and 127807 and 127707 at Lower Sheep Creek. Here we report some lysimeter results, described in the previous section, that are relevant to the neutron probe calibration. Since the lysimeters provide information only on the change in the total soil profile water storage with time (ΔW, mm), we converted measured θ's into soil profile water storage values. To do this we assumed that the neutron probe reading for each depth represented a specific depth increment of soil. The water storage for each depth increment was calculated by multiplying the neutron probe measured θ for a depth by the depth increment. Each depth increment was then added to produce a single soil profile water storage. Thus, the 0.15 m reading represented soil water from 0 to 0.230 m, the 0.305 m depth represented soil water between 0.230 and 0.460 m, the 0.610 m depth between .460 to 0.750 m and the 0.915 m reading represented depth between 0.760 and 1.070 m. Values for ΔW were then calculated relative to the first recorded readings of the calender year.

A comparison of the neutron probe data in matching lysimeters indicates a close agreement (Figure 3 a,b). Regression of the two matching probes against each other produced high r^2 values (0.98 at Reynolds Mountain and 0.96 at Lower Sheep Creek), slopes near 1.0 (0.96 at Reynolds Mountain and 1.03 at Lower Sheep Creek) and y-intercept values near 0 (-0.11 at Reynolds Mountain and 0.18 at Lower Sheep Creek). This demonstrates the reproducibility of the neutron probe readings and shows that the water inputs and losses for the matching lysimeters must be approximately equivalent.

We then compared the average ΔW calculated from neutron probe data with the ΔW measured with the best operating lysimeter at each site. In general, there was good agreement between the two methods of determining changes in soil water storage (Figure 4 a,b). These data have been described in detail in the previous section, but the implication for neutron probe calibrations is that, since ΔW calculated from two independent sources are in close agreement, they are probably accurate. Thus, the slopes (not necessarily the y-intercept) of the neutron probe calibration curves must be accurate.

Some of the scatter observed in Figure 4 is due to inherent limitations of the neutron probe. For example, because neutrons near the surface are lost to the atmosphere, surface measurements require a specific approach not used in this study, so that surface θ changes were not well measured. Also, the approach assumes a smooth distribution of water in the profile and abrupt wetting and drying fronts will lead to errors. Finally, the bottom 0.10 m of the lysimeters are not accounted for.

It should also be noted that, for purposes of ΔW calculations, the neutron probe has an inherent advantage over other monitoring instruments in that it has a relatively large measurement volume. The actual volume sampled varies with water content, but is generally has a radius on the order of 0.15 m. Thus, 0.30 m measurement spacings result in a more or less continuous sampling volume the over length of the access tube. Other instruments, such as the time domain reflectometry, use waveguides that are usually inserted horizontally into a soil pit face and measure narrow “slices” of the soil profile that have a measured volume almost two orders of magnitude less than the neutron probe. Another advantage of the neutron probe is that, unlike most other instruments, it is not affected by soil freezing.

3.8 Absolute Calibration

The analyses presented indicate that: (i) the calibrations are highly precise; (ii) the data are reasonably self consistent with some bias introduced by the different instruments used; (iii) the measurements are highly reproducible; and (iv) the calibration slopes used are approximately correct. This all indicates that these data can be used to accurately calculate changes in θ.

There are, however, no data that indicate how close the measurements of θ are to the "true" value. That is, how much bias was introduced by the calibrations. This is not unusual for neutron probe data. As Williams and Sinclair (1981) noted, "Attempts to estimate bias in the neutron method are conspicuous by their absence from the literature". Some samples were collected in an attempt to "check" the calibrations. It showed considerable variation between gravimetrically determined θ and that calculated from neutron probe measurements, but was inconclusive due to the high variability of the data collected and the difficulty of comparing the same measurement volume. This high variability, the typically high coarse fragment content (which makes sampling difficult), and strongly contrasting soil horizons provide considerable obstacles for absolute calibration of the RCEW soils.

3.9 Other Considerations

The data have been checked for unreasonable values. In most cases those resulted from transposition errors. However, this checking was done to different standards by different individuals over the years, so that some "bad" values may persist, especially prior to 1975. Also note that errors in the larger digits are most likely to be detected.

It was noted that some of the stops on the cables that were set to establish the measurement depths migrated or slipped slightly with time so that, after a few years the measurement may be 0.02-0.03 m deeper than reported. This would not be critical in many soil profiles, but where there are abrupt soil boundaries it might be. Thus, we sometimes observed either upward or downward changes in θ when probes were changed from probe 606 to probe 607, which have the same measurement geometry. Also, there were times that it was necessary to make repairs to the access tubes themselves as animals, humans and vehicles trampled an exposed aluminum access tube. This could result in slight changes in the measurement depth.

Also note that the weather code that is included was “officially” changed twice (Appendix) but some of the field personnel apparently continued to use the old system for some time after that. Thus, in some cases the weather code data may not be correct.

3.10 Example Data

Despite the limitations described above, the soil water data presented represent an exceptionally long term, continuous high quality effort that provides data that is virtually unique. We present some of the data in graphical form by way of illustration. In the first case we show data from tube 098897 (Figure 8). Between 1/1/73 and 12/30/96, 526 readings were taken at each of five depths, 0.15, 0.305, 0.610, 0.915, and 1.220 m. The 0.15 m water contents are the most dynamic showing a pronounced annual cycle which peaks in late winter to early spring, as would be expected in a climate of sparse summer rain such as the RCEW. At increasing depth, the amplitude of the cycles is reduced and many peaks disappear entirely, indicating that the annual wetting front failed to arrive at that depth. The observed peaks are also displaced to the right with increasing depth. Thus, while the 0.15 m depth peak for 1978 is in February, the peak at 1.22 m is about three months later. Note that there is a discernable drop in calculated water content at the 0.61 m depth on 1/1/79 that is probably attributable to the change in instruments (492 to 607). This drop is not so evident at the other depths.

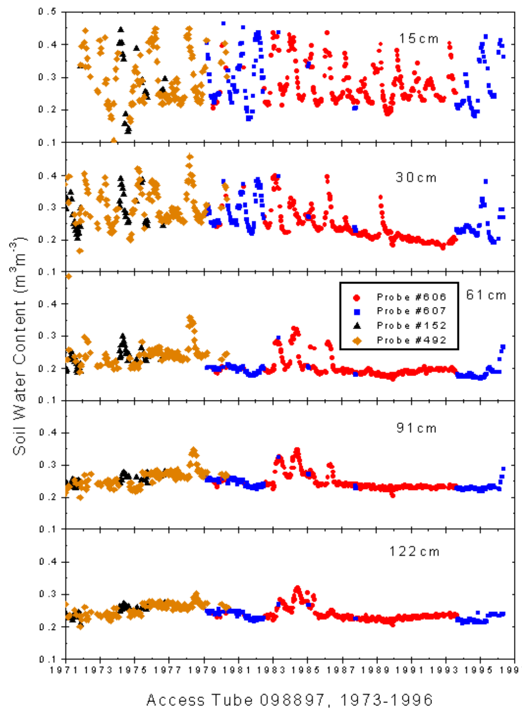

Figure 8. Soil water content at multiple depths over a 23 year period at access tube 098897 at Nancy Gulch.

Another view of the data is with depth within a given season (Figure 9). In 1993 there was a significant amount of precipitation and snowmelt between 3 March and 18 March at Lower Sheep Creek (117287). This resulted in a progressive increase in surface water content from 0.12 to 0.25 m^3m^{-3} as well as infiltration to a depth of about 0.61 m. As the season progressed, surface water contents decreased and water slowly redistributed in the profile until 25 May, when the wetting front had reached a depth of 1.52 m.

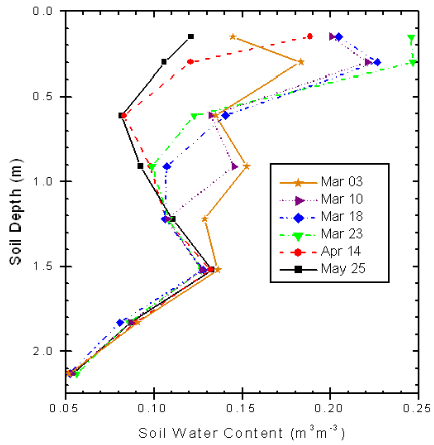

Figure 9. Infiltration during a single season at access tube 117287 at Lower Sheep Creek during 1993.

4. SOIL TEMPERATURE

4.1 Overview

Soil temperature exerts a strong and often overlooked role in a number of critical processes. The mineralization of plant nutrients, such as nitrogen, along with the consequent liberation of carbon dioxide, is strongly temperature dependent. Other biological processes, such as plant root growth and seed germination are also dependent on temperature. Surface energy balance, which supplies an important and poorly understood feedback to atmospheric forcings, is also directly related to soil temperature. Soil temperature has added significance in the RCEW and many relatively high latitude or elevation locations due to the impact of soil freezing on hydrologic processes.

4.2 Data Collection

Long term soil temperature data have been collected at five sites, Flats, Nancy Gulch, Quonset, Lower Sheep Creek, and Reynolds Mountain, for varying periods and depths (Table 7). Each temperature profile is located at either a long-term weir site (e.g., Flats and Nancy Gulch) or at a long-term climate station site (e.g., Quonset, Lower Sheep Creek and Reynolds Mountain). In every case there is at least one neutron access tube and precipitation gauge in close proximity and complete climate station information either at the site or reasonably close. All profiles are located on nearly level slopes.

Table 7. Location of soil temperature sites.

	UTM Coordinates and Elevation (m)					
	GPS measured			DEM		
Site	Easting	Northing	Elevation	Easting	Northing	Elevation
Flats	521391	4786033	1188	521400	476040	1186
Quonset	520367	4783418	1207	520380	4783430	1202
Nancy Gulch	523429	4779412	1420	523440	4779410	1406
Lower Sheep Creek	521742	4776189	1652	521730	4776200	1653
Reynolds Mountain	519693	4767923	2097	519690	4767920	2097

The temperature sensors used were YSI (Yellow Springs Instruments, Yellow Springs, OH) two-thermistor composite thermolinear components accurate to $\pm$ 0.15 °C. Data were originally collected by a connecting a hand-held voltmeter to the sensor leads. Individual sensors at different depths were read using a manual switch. These data were collected once each week and the time was recorded. At some sites the switches were bypassed and hooked up to data loggers of various design resulting in more frequent (either one or four hour) recording intervals (Table 8).

Table 8. Soil temperature data intensity.

Station (ID)	Period	Interval	Depths (cm)
Flats (057x96)	Feb 1981–Sept 1992	weekly	10,30,60,90,120,180
	Oct 1992–Oct. 1996	1-hr	5,10,20,30,50,60,90,120,180
Quonset (076x59)	Jan 1981–Aug 1985	4-hr	2.5,5,10,20,30,40,55,70
	Aug 1985–Jun 1994	1-hr	2.5,5,10,15,20,30,40,60,70,90
	Jun 1994–Oct. 1996	1-hr	5,10,20,30,40,50,60,90,120,180
Nancy Gulch (098x97)	Nov 1981–Jun 1985	1-hr	10,30,60,90,120
	Jun 1985–Sep 1990	1-hr	5,10,30,60,90,120,180,240
	Sep 1990–Oct. 1996	1-hr	5,10,20,30,40,50,60,90,120,180
Lower Sheep Creek (127x07)	Jan 1982–	weekly	10,30,60,90,120,180,240
	Dec 1984–Sep 1990	1-hr	10,30,60,90,120,180,240
	Sep 1990–Oct. 1996	1-hr	5,10,20,30,40,50,60,90,120,180
Reynolds Mtn. (176x14)	Dec 1981–Aug 1990	weekly	10,30,60,90,120,180,240
	Aug 1990–May 1992	weekly	5,10,20,30,40,50,60,90,120,180
	June 1992–Oct. 1996	1-hr	5,10,20,30,40,50,60,90,120,180

Prior to 1990, soil temperature sensors were installed by attaching the sensors to a 0.05-m diameter wooden pole at the desired depths; drilling a hole a with a drill rig (the soils in the RCEW are very rocky); inserting the pole in the drilled hole and backfilling. In many cases the performance of sensors was observed to deteriorate slowly over time. Apparently water gradually entered the sensors as the potting compound used to seal the sensors slowly deteriorated, thus altering the circuit resistance of the sensors.

In 1990 new sensors were installed at all sites. These were of the same design but a few changes were made. First, the potting compounds used were changed based on considerable experience gained since the previous installation. Second, all sensors were read with Campbell data loggers, and recorded hourly. (Each hourly reading is the average of 6 ten minute readings such that the 12:00 reading is the average of the 11:10, 11:20, 11:30, 11:40, 11:50 and 12:00 readings). Third, the sensors were installed horizontally into the face of an exposed backhoe pit face much as suggested by Livingston (1993). And fourth, the sensor depths were changed somewhat (Table 8). The sensors have generally performed very well since the latest installation.

4.3 Example Data

The soil temperature data are listed by site ID (using six digit nomenclature described by Seyfried et al., 2000) and measurement frequency (hourly or daily). For each measurement the date, time and temperature in °C are provided. We made a concerted effort to detect gradual deterioration of sensors and eliminate those from the data set. Some such errors, in subtle form, may still exist. We made less of an attempt to eliminate localized “spikes”, which should be obvious to the user. We made no effort to interpolate between dates of missing data.

Two figures are included to illustrate the kind of soil temperature data collected. One (Figure 10) shows the effects of snow and ice formation on soil temperature dynamics. Nancy Gulch is at a lower elevation than Reynolds Mountain and hence the mean annual air temperature is considerably warmer. Temperatures plotted were recorded at 12 AM, as opposed to hourly, to eliminate diurnal fluctuations which obscure the longer term patterns. On 1 October the 0.90 and 1.80 m depth temperatures were about 17 °C at Nancy Gulch and 12 °C at Reynolds Mountain. It is apparent that the two sites experience the same general weather frontal patterns, as evidenced by the soil temperature dip at both sites on 1 June. Immediately prior to 1 November, both sites experienced cool weather precipitation. At Nancy Gulch the precipitation was mostly rain. The near surface temperature quickly dropped below freezing. Diurnal fluctuations were effectively damped while the soil was frozen. Near 15 February snow covered the site and soil temperatures stabilized with a slightly positive gradient. By contrast, the same precipitation event near 1 November was snow at Reynolds Mountain. Surface (0.05 m) soil temperatures rapidly descended to near 0 °C as snow provided a 0 °C surface boundary condition. Temperatures were maintained above 0 °C due to the insulating effect of the snow, but gradually converged on that value.

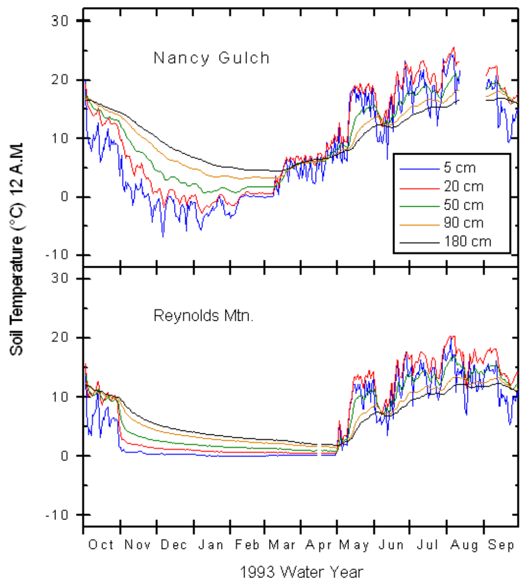

Figure 10. Comparison of soil temperature dynamics at Nancy Gulch and Reynolds Mountain during 1993.

The second figure (Figure 11) illustrates interannual soil temperature variations at a site. Temperatures at noon every 7^{th} day are plotted. The expected seasonal fluctuations are obvious, with minima near the beginning of each year at 0.1 m. The temperature range of each annual cycle decreases with depth in an approximately exponential fashion (Jury et al., 1991) from about 29 °C at 0.1 m to about 15 °C at 1.2 m. Peaks are also damped with depth and appear over one month later at 1.2 m than at 0.1 m. Perhaps a little less widely appreciated is the high degree of interannual stability in the timing and magnitude of soil temperature. Note also the missing data intervals, which is typical.

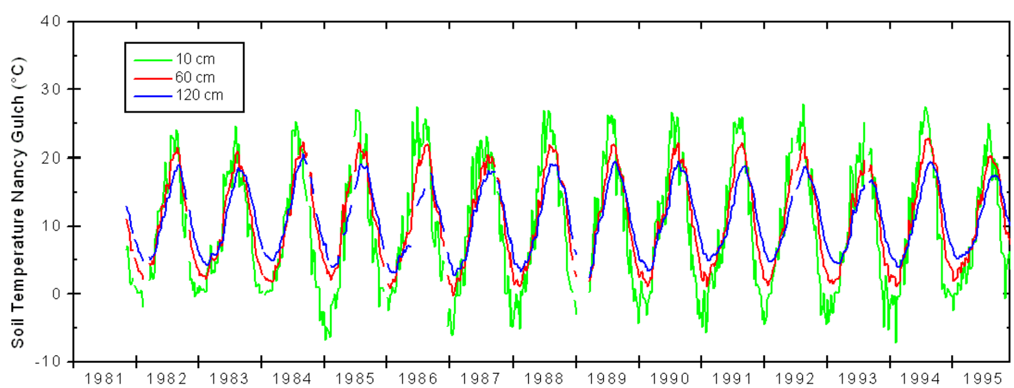

Figure 11. Interannual soil temperature variation with depth at a single site, Nancy Gulch.

5. DATA AVAILABILITY

Lysimeter data from two sites, soil moisture data from six sites, and soil temperature data from five sites are available from the anonymous ftp site ftp.nwrc.ars.usda.gov maintained by the USDA Agricultural Research Service, Northwest Watershed Research Center in Boise, Idaho, USA. Lysimeter and soil moisture data are located in the directory publicdatabase/soilmoisture, and soil temperature data are located in the directory publicdatabase/soiltemperature, in ASCII files that have been compressed using a "zip" utility. Each file has a <26>-line ascii header providing brief information on file contents, location (Easting and Northing, UTM zone 11), both the GPS elevation and the DEM elevation (see Seyfried et al., 2000), time format, and period of record, column contents and units, missing data key, contact, citation and disclaimer information. An ASCII README file in each directory gives a detailed description of the file formats and contents.

Both the daily and hourly lysimeter data are stored in two separate files (one for each site) identified by the data type and station ID (eg.: "daily127x07lysimeter.txt" or "hourly127x07lysimeter.txt"). Each record in the daily lysimeter file consists of a line containing month, day, year, lysimeter water content (mm), lysimeter code, lysimeter water content (mm), lysimeter code. Each record in the hourly lysimeter file consists of a line containing month, day, year, hour, minute, lysimeter water content (mm).

Neutron probe soil moisture data are stored in eighteen separate files identified by site and tube location (eg.: "neutronprobesoilwater057896.txt" or "neutronprobesoilwater057c96.txt"). Each record in these file consists of a line containing month, day, year, hour, minute, probe ID, ground condition code, sky condition code, precipitation condition code, soil moisture (% by volume) at 15cm, 30cm, 61cm, 91cm, 122cm, 152cm, 183cm, 213cm, 244cm, 274cm (depending on access tube depth), standard count, count at 15cm, 30cm, 61cm, 91cm, 122cm, 152cm, 183cm, 213cm, 244cm, and 274cm (depending on access tube depth). Soil descriptions associated each access tube are found in a database file neutronprobesoils.dbf and are described in neutronprobesoils.txt found at the same site.

Weekly soil temperature data are stored in three separate files and hourly soil temperature data are stored in five separate files identified by the data type and station ID (eg.: "weekly057x96soiltemperature.txt" or "hourly057x96soiltemperature.txt"). Each record in the weekly and hourly soil temperature files consists of a line containing month, day, year, hour, minute, soil temperature (C) at 5cm, 10cm, 20cm, 30cm, 50cm, 60cm, 90cm, 120cm, and 180cm.

Any publications which are generated from these data should cite this publication, and acknowledge the USDA-ARS Northwest Watershed Research Center as the source. In addition we request that you notify NWRC of all publications, including theses and dissertations, which use or refer to these data. Citations may be sent by email to: publicdatabase@nwrc.ars.usda.gov or by mail to: USDA-ARS Northwest Watershed Research Center, 800 Park Blvd., Suite 105, Boise, ID 83712-7716. Your cooperation in this matter will promote further research and cooperation, help to validate the usefulness of the ARS experimental watersheds and data collection activities, and influence agency policy regarding future data collection.

6. DISCLAIMER

The mention of trade names or commercial products does not constitute endorsement or recommendation for use. The Agricultural Research Service (ARS) is a research organization. There are no legal mandates for the agency to collect or to distribute data collected for specific research projects. These data are being made available to the research community to promote the general knowledge of the processes relating to our country's natural resources.

7. APPENDIX

Table A1. Weather Codes Reported.

1st Digit: **Weather**	Before 1/12/77	Between 1/12/77 and 2/24/82	After 2/24/82
1	No rain	same	same
2	Sprinkle	same	same
3+	light shower	same	same
4	slight, steady rain	same	same
5	medium shower	same	same
6	heavy rain	same	same
7	snow shower	same	same
8	snow on ground	discontinued	discontinued

2nd Digit: **Sky Conditon**	Before 1/12/77	Between 1/12/77 and 2/24/82	After 2/24/82
1	Clear	same	same
2	High Cloud	same	same
3	Moderate cloud cover	same	same
4	scattered high clouds	same	same
5	high dense clouds	same	same
6	low dense clouds	same	same
7	fog	same	same

3rd Digit: **Surface Soil Water**	Before 1/12/77	Between 1/12/77 and 2/24/82	After 2/24/82
1	dry	same	same
2	moist	same	same
3	wet	same	same
4	saturated	same	same
5		snow too deep	same
6			snow cover, dry soil
7			snow cover, moist soil
8			snow cover, wet soil

8. ACKNOWLEDGMENTS

Installation of the instrumentation used to collect this data was a major task, but nothing compared to the work of maintaining the effort over a long time period. Ultimately, the key to this data collection program was the individuals who did the field work. Many individuals were involved in this task, but none more than Delbert Coon. In addition to maintaining a regular schedule visiting each site at least biweekly, year round, he helped install the lysimeters, neutron access tubes, and soil temperature profiles, served as the nuclear safety officer, and generally maintained data continuity. Mike Burgess was responsible for maintaining the electronics at a time when they were being developed. This is a story in itself, but before there were commercial datalogers, Mike was building his own and operating them in the RCEW. Others who have contributed many hours to this database include Dave Robertson, Sue Stillings, April Barrington and much of the scientific staff that has worked at the RCEW over the years.

9. REFERENCES

Chanasyk, D. S., and M. A. Naeth, Field measurement of soil moisture using neutron probes. *Canadian Journal of Soil Science* 76, 317-23,1996.

Clark, P.E. and M.S. Seyfried. Point quadrat validation for leaf area index assessment in shrub steppe communities. Submitted to the Journal of Range Management.

Gardner, W. H. Water Content. *Methods of Soil Analysis Part 1-Physical and Mineralogical Methods.* 2 ed., ed A. Klute, 493-544. Madison, WI: ASA, 1986.

Gardner, W., and D. Kirkham. Determination of soil moisture by neutron scattering. *Soil Sci.* 73, 391-401, 1952.

Greacen, E. L., editor. *Soil water assessment by the neutron method.*, 140 pp. CSIRO, Melbourne, Australia: 1981.

Hanson, C.L., Precipitation monitoring at the Reynolds Creek Experimental Watershed, Idaho, USA, U.S. Dept. of Agriculture, Agricultural Research Service, Northwest Watershed Research Center, Boise, ID, *Technical Bulletin NWRC 2000-4*, 2000.

Hanson, C. L., D. Marks, and S. S. Van Vactor., Climate monitoring at the Reynolds Creek Experimental Watershed, Idaho, USA, U.S. Dept. of Agriculture, Agricultural Research Service, Northwest Watershed Research Center, Boise, ID, *Technical Bulletin NWRC 2000-6*, 2000.

Howell, T.A., Schneider, A.D., and Jensen, M.E., History of lysimeter design and use for evapotranspiration measurements, in *Lysimeters for Evapotranspiration and Environmental Measurements*, edited by R. G. Allen, T. A. Howell, W. O. Pruitt, I. A. Walter, and M. E. Jensen, pp. 1-9, ASCE, New York, 1991.

Jury, W.A., W.R. Gardner and W.H. Gardner, *Soil Physics*, 328 pp., John Wiley, New York, 1991.

Kruse, E. G., and C. M. U. Neale. Hydraulic weighing lysimeter errors, in *Lysimeters for Evapotranspiration and Environmental Measurements*., edited by R. G. Allen, T. A. Howell, W. O. Pruitt, I. A. Walter, and M. E. Jensen, pp. 133-141, ASCE, New York, 1991.

Livingston, N.J., Soil Temperature. MR. Carter editor, Lewis Publishers, Boca Raton, FL. In Soil Sampling and Methods of Analysis. 673-682,1993.

Marks, D., K. R. Cooley, D. C. Robertson, and A. Winstral, Snow monitoring at the Reynolds Creek Experimental Watershed, Idaho, USA, U.S. Dept. of Agriculture, Agricultural Research Service, Northwest Watershed Research Center, Boise, ID, *Technical Bulletin NWRC 2000-5*, 2000.

Rawls, W. J., J. F. Zuzel, and G. A. Schumaker. Soil moisture trends on sagebrush rangelands, *J. Soil and Water Conser.,* 28, 270-272, 1973.

Reginato, R. J., and F. S. Nakayama, Neutron probe calibration based on plastic transfer standards. *Soil Sci.,* 145, 381-84,1988.

Scheider, A.D. and T.A. Howell. Large, monolithic, weighing lysimeters, in *Lysimeters for Evapotranspiration and Environmental Measurements*, edited by R. G. Allen, T. A. Howell, W. O. Pruitt, I. A. Walter, and M. E. Jensen, pp., 37-45, ASCE, New York,1991.

Seyfried, M., Spatial variability constraints to modeling soil water at different scales, *Geoderma* 85, 231-54,1998.

Seyfried, M. S., R. C. Harris, D. Marks, and B. Jacob, A geographic database for watershed research, Reynolds Creek Experimental Watershed, Idaho, USA, U.S. Dept. of Agriculture, Agricultural Research Service, Northwest Watershed Research Center, Boise, ID, *Technical Bulletin NWRC 2000-3*, 2000.

Sommers, L.E., C.M. Gilmour, R.E. Wildung S.M. Beck. The effect of water potential on decomposition processes in soils. In Parr, J.E., Gardner, W.R., Elliot, L.F. Water potential relations in soil microbiology SSSAJ Special Publication #9 97-117.SSSA Madison, WI, 1981.

Stephenson, G. R., and J. F. Zuzel, Groundwater recharge characteristics in a semi-arid environment of southwest Idaho, *J. of Hydrol.* 53, 213-227, 1981.

Tanner, C. B., Measurement of Evapotranspiration, in *Irrigation of agricultural Lands edited by* R.M. Hagan, H.R. Haise, and T. W. Edminster, pp.,534-7411, ASA, Madison, WI, 1967.

Williams, J., and D. F. Sinclair, Accuracy, bias and precision in *Soil water assessment by the neutron method, edited by* E. L. Greacen, pp., 35-49, CSIRO, Melbourne, Australia, 1981.