A Soil Moisture Climatology of Illinois

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ABSTRACT

Ten years of soil moisture measurements (biweekly from March through September and monthly during winter) within the top 1 m of soil at 17 grass-covered sites across Illinois are analyzed to provide a climatology of soil moisture for this important Midwest agricultural region. Soil moisture measurements were obtained with neutron probes that were calibrated for each site. Measurement errors are dependent upon the volumetric water content with errors less than 20 percent when soil moisture is above 10 percent of soil volume. Single point errors in moisture measurements from the top 1 m of soil range from 6 percent to 13 percent when volumetric soil moisture is 30 percent of soil volume. The average depletion in moisture between winter and summer over the 10-year period for the top 2 m of soil in Illinois was 72.3 mm. Three-quarters of this decrease occurred above 0.5 m and only 5 percent occurred between the 1.0-m and 2.0-m depths. The average moisture decrease between winter and summer during a wet year (1985) and a drought year (1988) in the top 2 m of soil was 64 percent and 204 percent of the average for the 10-year period, respectively. Seasonal means in soil moisture averaged for the state show the effects of different seasons and soil types on soil moisture. In the winter and spring a latitudinal gradient exists with the wetter soils in the southern part of the state. During summer and autumn there is a longitudinal gradient with the wetter soils in the eastern half of the state. The longitudinal gradient is closely associated with the depth of loess deposits. A north to south latitudinal gradient of soil moisture variability for the summer season is also evident in the 10 yr of records. A comparison of time series of soil moisture from sites with differing soil texture shows that a silty loam soil holds 2 to 3 times more water in the top 1 m than a loamy sand soil. Time series of soil moisture indicate that seasonal variations in water in the top 1 m at a grass-covered site was 1 to 2 times greater than at an adjacent nonvegetated site.

1. Introduction

Provision of the best possible climate information to public and private users is dependent, first and foremost, on the acquisition of high-quality data. The usefulness of this information depends on the selection of the appropriate climatic factors to measure. In addition, the quality of climatic information benefits greatly from an understanding of temporal and spatial patterns and relationships in the historical data (Lamb et al. 1985).

Soil moisture is an important climatic factor for which high-quality data demanded by users, especially in the agribusiness sector, is not generally available (Wendland and Vogel 1986; Kunkel 1990). Cognizance of the moisture content of the upper portion of the soil profile is critical to the scheduling of field efforts by farmers and is an important input to the crop yield models that are used by grain and brokerage companies and their consultants. Surface water management decisions are also based on knowledge of soil moisture content, especially when conditions are extreme. In addition, further refinement of general circulation models for comprehending man-induced climate processes and their implications depends to a large extent upon a better understanding of temporal and spatial distributions of a number of surface parameters, including moisture in the upper layer of the earth's surface (Delworth and Manabe 1988).

The dearth of accurate and timely soil moisture information is a direct result of the expense and difficulty of obtaining high-quality soil moisture measurements at useful temporal and spatial scales. For this reason, most soil moisture information is output from computer models that are based on a limited number of soil moisture measurements at a few sites over one or two growing seasons (e.g., Ritchie 1972; Robinson and Hubbard 1990; Kunkel 1990). An exception to this generalization is the unique dataset of gravimetric soil moisture measurements from sites with natural cover throughout the Soviet Union (Vinnikov and Yeserkepova 1991). Accurate and nondestructive measurements of soil moisture require the use of expensive

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electronic equipment such as a neutron probe or time domain reflectometry systems.

Accurate representation of soil moisture is difficult because of its large temporal and spatial variability. The physical properties that determine the moisture storage characteristics of soil vary tremendously over short distances, both vertically throughout the upper portion of a soil profile and horizontally across the earth's surface among soil units. Precipitation and groundwater inputs to the upper soil and evapotranspiration and deep percolation outputs of water from the soil are also highly variable both through time and across space.

In response to the increasing demand for accurate and timely climate information at fine temporal and spatial resolution, the Illinois State Water Survey initiated the Illinois Climate Network (ICN) in 1981. The ICN provides measurements of solar radiation, soil temperature and moisture, screen height temperature and humidity, and wind speed and direction on a continuous or (in the case of soil moisture) frequent basis. Since that time, a neutron probe system has been used to measure soil water content at each ICN site at regular intervals throughout the year with a fine vertical resolution to a depth of 2 m. By 1983, soil water content was being measured at 15 locations across the state and two more sites were added in 1986 (Fig. 1).

The purpose of this study is to analyze the patterns and relationships contained within this soil moisture data. Although this Illinois record is only 10 yr long, it is the most comprehensive set of continuous soil moisture measurements available for an important Midwest agricultural region. Analysis of these historical data should improve utilization of year-to-date and now-only soil moisture information by agribusiness and surface water managers, and provide large-area measures of soil moisture variability that could help improve crop-yield and general circulation models.

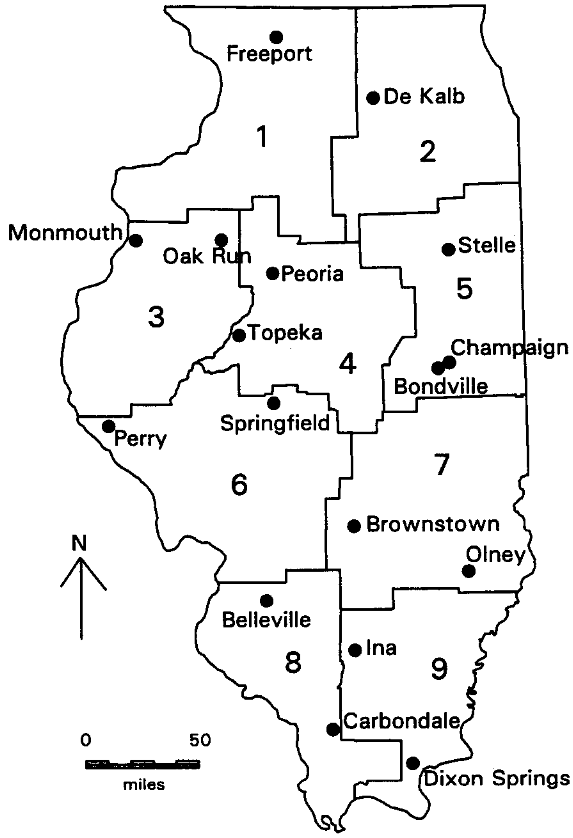

FIG. 1. Location of ICN soil moisture measurement sites throughout Illinois.

2. Data and methodology

The name, location, and beginning date of record for the ICN soil moisture measurement sites are provided in Table 1. The soils at each station (Table 2) are characteristic of the soils in the vicinity of the sites. With the exception of the Plainfield sand site at Topeka, the soil textures were predominately silty loam or silty clay loam.

Soil moisture was measured within grass plots using a Troxler[1] Neutron Depth Probe and a Troxler Neutron Surface Probe. Measurements were taken within 11 soil layers to a depth of 2 m; the first in the top 0.1 m of the profile, then every 0.2 m from a depth of 0.1 m through 1.9 m, and the last in the layer between 1.9 m and 2.0 m. Soil moisture in the top 0.1 m was measured with the surface neutron probe containing a neutron source and counter positioned parallel to the soil surface and covered by a heavy plastic shield. Neutrons from the surface probe are reflected to the counter from the top 0.1 to 0.15 m of soil. Soil moisture measurements from the soil layers below 0.1 m were obtained by lowering a neutron source and counter into a vertical, 0.058-m-diameter, aluminum tube permanently installed in the soil. The depth probe measures a spherical soil volume with a radius of 0.10 to 0.15 m.

Neutron probes use a source of high-energy neutrons and an electronic counter of low-energy neutrons to measure water content (Troxler Electronic Laboratories 1980). Collisions of high-energy neutrons preferentially with hydrogen nuclei from water molecules in the surrounding soil cause the high-energy neutrons to lose much of their energy and randomly reflect the lower-energy neutrons back to the counter. The counter records the number of low-energy neutrons reflected toward the access tube.

Because the mass of a neutron is similar to that of a hydrogen atom, hydrogen is the most effective element at slowing neutrons. Water and organic matter in the soil contain hydrogen atoms. Hydrogen atoms

[1] Reference to brand names or companies is made for information purposes only and does not imply endorsement of these companies or brands over any other company or brand.

TABLE 1. Name, location, and beginning date of record for Illinois soil moisture monitoring stations. The stations are listed in order from west to east and north to south across the state. Stations can be identified on the map in Fig. 1 by site name.

Site	County	Site code	Latitude (N)	Longitude (W)	Elevation (m)	Beginning of record
Freeport	Stephenson	FRE	42°14′	89°40′	265	15 Apr 1982
De Kalb	De Kalb	DEK	41°51′	88°51′	265	21 May 1981
Monmouth	Warren	MON	40°65′	90°41′	229	19 Jun 1981
Oak Run	Knox	OAK	40°58′	90°09′	265	1 Jun 1981
Peoria	Tazewell	ICC	40°42′	89°32′	207	25 Oct 1982
Stelle	Ford	STE	40°25′	89°19′	207	31 Mar 1986
Topeka	Mason	MTF	40°18′	89°54′	152	1 Jun 1981
Bondville	Champaign	BVL	40°03′	88°52′	213	19 Feb 1981
Champaign	Champaign	CMI	40°07′	88°14′	219	26 Jun 1986
Perry	Pike	ORR	39°48′	90°50′	206	6 May 1981
Springfield	Sangamon	LLC	39°31′	89°37′	177	22 Jul 1982
Brownstown	Fayette	BRW	38°57′	88°57′	177	30 Apr 1981
Olney	Richland	OLN	38°44′	88°06′	134	23 Jul 1982
Belleville	St. Clair	FRM	38°31′	89°53′	133	13 May 1982
Ina	Jefferson	RND	38°08′	88°55′	130	5 Aug 1982
Carbondale	Jackson	SIU	37°43′	89°14′	137	24 Nov 1982
Dixon Springs	Pope	DXG	37°27′	88°40′	165	29 Apr 1981

are also present as free ions that help determine the soil pH. Changes in organic matter and pH in soils usually occur gradually over many years. Consequently, there is generally a strong linear relationship between variations in soil water content and the neutron count ratio. The neutron count ratio is the number of slow neutrons reflected back to the counter from the soil divided by the number of slow neutrons reflected back to the counter from a dense plastic shield that serves as a standard. However, this relationship varies greatly among sites because of different soil pH and organic matter as well as other elements that slow neutrons. Therefore, the neutron probe counts should be calibrated to gravimetric measurements of soil moisture at each site.

Calibration of the neutron probe counts at each site was accomplished by taking soil cores on two occasions concurrent with neutron probe measurements. The cores were used to characterize the soil bulk density and volumetric water content of the sites and to establish the linear relationship between the neutron count ratio and soil water content. The first set of cores were taken as undisturbed samples when the soil was very dry during the summer drought of 1988 (Hollinger and Isard 1989). Three undisturbed samples from each site were used to determine the mass water content

TABLE 2. Soil series, family, texture, and total porosity in the top 1 m at the ICN sites.

Site	Series	Family	Texture	Total porosity (mm)
Freeport	Dubuque	fine silty, mixed, mesic Typic Hapludalfs	silt loam	523
De Kalb	Flanagan/Drummer	fine, montmorillonitic, mesic Aquic Argiudolls	silt loam	515
		fine silty, mixed, mesic Typic Haplaquolls	silt clay loam	
Monmouth	Muscatine	fine silty, mixed, mesic Aquic Hapludolls	silt loam	521
Oak Run	Rozetta	fine silty, mixed, mesic Typic Hapludalfs	silt loam	470
Peoria	Clinton	fine montmorillonitic, mesic Typic Hapludalfs	silt loam	445
Stelle	Monee	fine, illitic, mesic Mollic Ochraqualfs	silt loam	435
Topeka	Plainfield	mixed, mesic, Typic Udipsamments	loamy sand	446
Bondville	Flanagan/Elburn	fine montmorillonitic, mesic Aquic Argiudolls	silt loam	504
		fine silty, mixed, mesic Aquic Argiudolls	silt loam	
Champaign	Drummer	fine silty, mixed, mesic Typic Haplaquolls	silt clay loam	543
Perry	Clarkesdale	fine montmorillonitic, mesic Udollic Ochraqualfs	silt loam	544
Springfield	Ipava	fine, montmorillonitic, mesic Aquic Argiudolls	silt loam	499
Brownstown	Cisne	fine, montmorillonitic, Mollic Albaqualfs	silt loam	504
Olney	Bluford	fine, montmorillonitic, mesic Aeric Ochraqualfs	silt loam	417
Belleville	Weir	fine, montmorillonitic, mesic Typic Ochraqualfs	silt loam	474
Ina	Cisne	fine, montmorillonitic, mesic Mollic Albaqualfs	silt loam	467
Carbondale	Parke	fine silty, mixed mesic Ultic Hapludalfs	silt loam	491
Dixon Springs	Grantsburg	fine silty, mixed, mesic Typic Fragiudalfs	silt loam	486

and bulk density of the soil in each 0.2-m layer. Mass water content was determined by weighing the soil samples while they were wet, drying them in an oven at a temperature of 105°C for 24 h, and reweighing the dried samples. Bulk density was determined from the weight and volume of the soil sample prior to oven drying. Volumetric water content (usually expressed in percent as the volume of water/volume of soil, or equivalently in millimeters as the depth of water in a soil column of specified depth) and porosity of the samples (expressed in millimeters as 1.0 bulk density 2.65^{-1}) were computed from the mass water content and bulk density (Campbell 1985). Total porosity, considered equivalent to volumetric water content at saturation, was determined by summing the equivalent depth in millimeters of the pore space over the six layers composing the top 1 m of the soil (Table 2). A second set of soil samples were taken when the soil was wet in the spring of 1989. The mass water content of these samples were determined and volumetric water content computed using the bulk densities determined from the first set of soil cores. Measurements from the five layers between 0.10 and 1.0 m for both the dry and wet calibration datasets were used to establish the linear relationship between the neutron depth probe count ratio and volumetric water content for each ICN site. The methodology used to extract undisturbed soil samples for computing soil bulk density (Hollinger and Isard 1989) proved to be inaccurate for sandy soils. Therefore, the mean of the calibration coefficients from the other 16 ICN sites was used for the Topeka site. Because of the small number of measurements for the surface layer (two neutron counts and six volumetric water content determinations for each site), a single linear relationship between the neutron surface probe counts and volumetric water content was determined by combining the surface-layer data from all the ICN stations except Topeka.

An estimate of the error associated with a neutron probe volumetric water content measurement (E in millimeters of water) in a soil layer with thickness L is given by:

$$E = L\frac{[2.3SE^2 + (0.0163M + 0.1651)^2]^{1/2}}{100}, \quad (1)$$

where SE is the standard error of the calibration coefficient expressed in percent, 2.3 is the critical value of the t statistic at $\alpha = 0.05$ with $n = 8$, $(0.0163M + 0.1651)$ is the error associated with the neutron source as determined by the manufacturer, and M is the volumetric water content in percent (Troxler Electronic Laboratories 1980). When measurements from more than one soil layer are used to determine the volumetric water content of a soil column, the measurement error estimate (E_c, in percent of volumetric water content) is the sum of the estimates of errors for each layer normalized by the total column volumetric water content and is given by

$$E_c = 100(\sum_{i=1}^{n} M_i)^{-1}(\sum_{i=1}^{n} E_i^2)^{1/2}, \quad (2)$$

where the subscripts represent the soil layers.

Each site was visited twice each month (the week of the 15th and the week of the last day of the month) during the months of March through September, and once each month during the last week of October through February. After each visit, the neutron count ratios obtained using the surface and depth probes were converted to total volumetric water content.

3. Results and discussion

The calibration coefficients (intercepts and slopes) from the linear relationships between neutron probe count and volumetric water content, coefficients of determination, and standard errors of the estimates of volumetric water content are presented in Table 3. In general, the relationships between the neutron depth probe counts and volumetric soil moisture were strongest where variations in volumetric soil moisture between the dry and wet sets of calibration samples and variations of moisture with depth in the top 1 m of soil were greatest. For example, at Ina, close to the shore of Rend Lake, the soil was relatively moist throughout the entire profile to a depth of 2 m even when calibration samples were obtained during the 1988 drought. Consequently the slope coefficient and coefficient of determination for Ina are low. The last column in Table 3 gives the measurement uncertainty for a volumetric water content observation of 30 percent of the soil volume [equation (2)] in the top 1 m of soil at each site. The uncertainty of the soil moisture measurements range from 5.6 percent to 12.9 percent for a volumetric water content of 30 percent of soil volume. The largest error is associated with the Plainfield sand soil at the Topeka site, underscoring the importance of obtaining site-specific measurements of bulk density.

Figure 2 shows the uncertainty associated with volumetric moisture measurements ranging from 5 percent to 50 percent of saturation throughout the top 1 m of soil averaged for all ICN sites (middle curve). The top and bottom curves represent estimates of uncertainty in the soil moisture measurements at Topeka and Perry, the sites with the largest and smallest measurement uncertainties, respectively. Measurement uncertainty increases dramatically with decreasing soil moisture because it is represented as a percent of volumetric water content. Over 95 percent of the water content measurements at sites with silt loam or silt clay loam soils (all ICN sites except Topeka) were greater than 20 percent of soil volume (Fig. 3) and consequently measurement uncertainties were usually less than 20 percent of volumetric water content. For more than 70 percent of the observations, soil water content measurements exceeded 30 percent of the soil

TABLE 3. Calibration coefficients for each site and estimates of the point measurement uncertainty based on a 1-m soil profile with a volumetric water content of 30 percent.

Site	Calibration coefficients		r^2	Std. err.	Measurement uncertainty
	Intercept	Slope	(%)		(%)
Freeport	−0.16206	0.762097	92.8	2.34	7.36
De Kalb	−0.03685	0.539677	70.5	3.58	10.50
Monmouth	−0.05010	0.590620	92.7	2.04	6.65
Oak Run	−0.06019	0.616035	96.3	2.10	6.80
Peoria	−0.13530	0.750457	78.4	3.48	10.18
Stelle	−0.09686	0.643103	72.5	3.49	10.29
Topeka	0.00225	0.478336	70.5	4.49	12.90
Bondville	−0.03033	0.579987	92.2	2.31	7.30
Perry	−0.07104	0.640366	95.9	1.56	5.59
Springfield	0.07075	0.443391	64.1	2.47	7.69
Brownstown	−0.00507	0.500732	92.8	2.81	8.54
Olney	0.16534	0.252367	65.3	2.76	8.41
Belleville	−0.11607	0.727183	96.0	1.75	6.00
Ina	0.16074	0.284056	49.8	2.76	8.40
Carbondale	−0.00313	0.520645	91.3	3.32	9.85
Dixon Springs	−0.06713	0.624197	95.4	1.95	6.44
Surface Probe	0.00000	0.925660	72.2	4.50	10.37

volume and consequently measurement errors were less than 10 percent of the volumetric soil moisture.

The means of the three lowest soil moisture observations at each level in the top 1 m of soil at each station (Table 4) reveal the extent to which the soils in Illinois dry during summer droughts and provide an indication of maximum errors associated with the neutron probe soil moisture measurements. Soil moisture at Belleville reached a minimum of 1.0 percent of soil volume at the 0.1–0.3 m depth. In general, minimum soil moisture measurements at the ICN stations were greater than 20% of soil volume below a depth of 0.5 m. These minimum values compare favorably with the air dry volumetric water content values between 1 percent and 5 percent of porosity given by Campbell (1985) and the 5 percent, 10 percent, and 20 percent of porosity values for permanent wilting point listed by Hanks and Ashcroft (1986) for sand, loam, and silty clay loam, respectively.

Soil moisture in the upper 1 m of soil averaged for all stations is shown for 1981 through 1991 in Fig. 4. Precipitation between soil moisture observations averaged for the ICN sites is presented for comparison. It should be noted that the record is only representative of the state after the summer of 1982, by which time 13 of the 17 ICN sites were installed (Table 1). The maximum value of soil moisture during spring displays little interannual variation. Soil moisture exceeded 341 mm (70 percent of saturation) during each of the last 10 years in Illinois, reaching a maximum of 391 mm (80 percent of saturation) early in the spring of 1988.

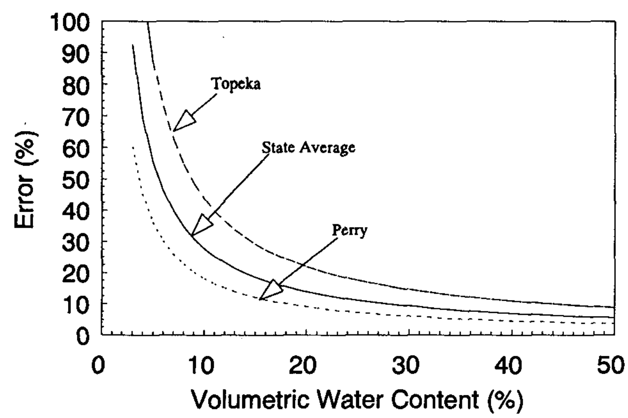

FIG. 2. Relationships between errors (percent) associated with soil moisture measurements and volumetric water content (percent of volume) of the soil.

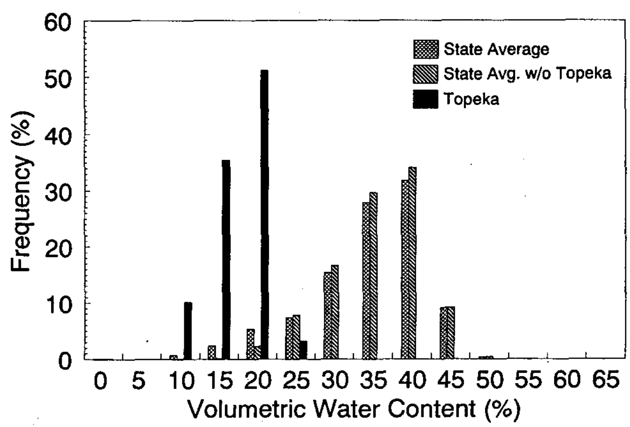

FIG. 3. Histogram showing percentage of soil moisture observations (frequency) by volumetric soil water content (percent of soil volume) averaged for all ICN sites, averaged for all ICN sites excluding Topeka, and for the Topeka station.

TABLE 4. Mean of the three driest soil observations in the top six soil layers at each of the Illinois soil moisture sites since January 1985. Soil moisture values are expressed as percent of soil volume.

	Soil layer					
Site	0–0.1 m	0.1–0.3 m	0.3–0.5 m	0.5–0.7 m	0.7–0.9 m	0.9–1.1 m
Freeport	10.9	6.0	8.0	10.6	18.2	25.1
De Kalb	13.8	7.2	18.7	24.0	24.5	26.8
Monmouth	12.5	11.4	14.5	17.0	19.7	25.1
Oak Run	6.5	4.0	14.9	27.5	27.2	32.0
Peoria	9.3	1.9	22.7	29.3	30.2	35.9
Stelle	14.6	11.5	22.1	21.8	21.8	21.9
Topeka	5.3	6.6	9.2	9.9	7.2	6.9
Bondville	11.4	12.6	18.2	27.1	23.6	28.1
Champaign	12.3	16.3	19.7	19.8	20.5	23.1
Perry	11.6	9.8	21.0	24.0	19.8	25.1
Springfield	11.9	23.3	28.6	32.0	28.3	31.0
Brownstown	8.3	6.4	10.3	26.1	26.6	29.8
Olney	7.2	21.4	24.9	32.0	30.3	29.5
Belleville	9.3	1.0	4.6	16.7	35.3	36.4
Ina	8.3	22.3	30.1	36.9	32.9	35.1
Carbondale	8.6	7.2	10.4	20.2	25.9	29.3
Dixon Springs	8.3	5.1	17.8	22.4	26.7	36.4
State average	10.0	10.2	17.4	23.4	24.6	28.1

Consequently, for the state as a whole, these data indicate that autumn, winter, and early spring precipitation is generally sufficient to recharge soil moisture in the top 1 m.

Inspection of Fig. 4 also reveals that there were four summer droughts (1983, 1984, 1988, and 1991) during the last 10 years, when on average, soil moisture decreased to below 279 mm (57 percent of saturation) in the top 1 m across Illinois. Soil moisture averaged across the state was lowest in mid-August 1983 (205 mm or 42 percent of saturation). In contrast, the dry conditions during the 1988 and 1991 summers tended to be more persistent. It should be noted that Wendland (1991) identified 1985, 1987, and 1988, but not 1983 and 1984 as drought years in Illinois on the basis of April to August precipitation (data from 1991 were not included in that study).

The annual cycle of moisture in the top 1 m of soil averaged for all ICN measurement sites is depicted in Fig. 5. The mean values and one standard deviation

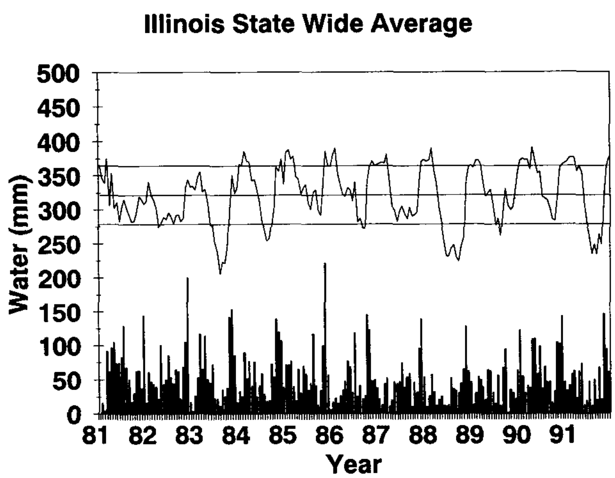

FIG. 4. Total water content in the top 1 m of soil (solid line) for the 17 ICN sites across Illinois for 1981–1992. The amount of precipitation for the periods between soil moisture measurements (usually 2 weeks) averaged for the same sites is presented for comparison (bars). The middle horizontal line represents 10-yr mean of all observations. The bottom horizontal line is the soil moisture level one standard deviation below the mean, and the top horizontal line is the soil moisture one standard deviation above the mean.

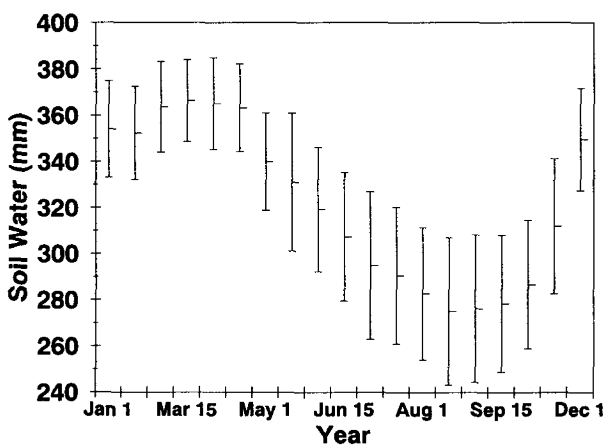

FIG. 5. Mean and standard deviation of soil moisture at each observation period. The mean and standard deviation of each period include all observations at the 17 stations between the start of record and December 1992.

TABLE 5. Mean soil moisture (mm) and changes in soil moisture between seasons (mm) for the 0–1.0-, 0–0.15-, 0.15–0.5-, 0.5–1.0-, 1.0–2.0-, and 0–2.0-m layers.

Layer (m)	Winter		Spring		Summer		Autumn	
	Mean	Change	Mean	Change	Mean	Change	Mean	Change
0–1.0	357.4	50.8	347.4	−10.0	288.1	−59.3	306.6	18.5
0–0.15	56.0	14.6	49.2	−6.8	33.6	−15.6	41.4	7.8
0.15–0.5	121.4	21.0	115.5	−5.9	89.7	−25.8	100.4	10.7
0.5–1.0	180.0	15.2	182.7	2.7	164.8	−17.9	164.8	0.0
1.0–2.0	346.9	9.4	353.9	7.0	343.5	−10.4	337.5	−6.0
0–2.0	704.3	60.2	701.3	−3.0	631.6	−69.7	644.1	12.5

(SD) above and below the mean were computed using all soil moisture observations for the ten-year measurement period. On average, soil moisture in the state is greatest in early spring (15 March) and lowest in late summer (15 August). Moisture begins to decline in the top 1 m of soil between mid-April and early May and begins to increase again in late September. The greatest recharge occurs during mid- to late autumn (October and November) and early winter (December). It is also clear that the variability of soil moisture conditions is twice as large in the summer (SD $\approx$ 30 mm) than during winter and early spring (SD $\approx$ 15 mm).

Volumetric soil moisture averaged for the ICN sites are shown in Table 5 for each season. Soil moisture is integrated over depths 0–1.0, 0–0.15, 0.15–0.50, 0.50–1.0, 1.0–2.0, and 0–2.0 m and the change in volumetric soil moisture from the previous season for each of the layers is given. Seasons are defined as winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). The values are the average of three observations during winter, six each in spring and summer, and four during the autumn season for each year in the record. It should be noted that soil moisture averages for the 0–1.0- and 0–2.0-m layers are greater for the winter than for the spring season even though maximum soil moisture for these layers occurs on 15 March (Fig. 5).

The average soil moisture depletion between the winter and summer seasons for the top 2 m of soil was 72.7 mm (Table 5). Three-quarters of this decrease occurred in the top 0.5 m of the soil with approximately one-third of the desiccation above the 0.15-m depth. Less than 5 percent of the soil moisture change from winter to summer occurred below 1 m. Table 6 shows average volumetric soil moisture values for a wet year (1985) and a dry year (1988) in Illinois. The decrease in soil moisture between winter and summer for the top 2 m of soil was 49.5 and 147.3 mm for the wet and dry years, respectively. The decrease in soil moisture from summer to winter in the top 2 m of soil in 1985 was only 69 percent of the average change for the 10-year record. eight Seventy-eight percent of this decrease occurred in the top 0.5 m of the soil with approximately 30 percent of the desiccation above 0.15 m. Approximately 4 percent of the soil moisture change during this time period occurred below 1 m. During the 1988 drought, desiccation in the top 2 m of soil was 204 percent of the average change for the 10-year record. Only 64 percent of the change from winter to summer occurred in the top 0.5 m of the soil, with 22 percent of the desiccation above 0.15 m. Approximately 10 percent of the soil moisture decrease between winter and summer occurred below 1 m.

Tables 5 and 6 also demonstrate the seasonal lag in soil moisture storage in the deeper layers compared to the top 0.5 m of soil. Soil moisture in the layers 0–0.15 m and 0.15–0.50 m peaked during the winter, declined through spring and summer, and recharged in the autumn. Peak soil moisture conditions in the

TABLE 6. Mean seasonal soil moisture (mm) for seasons during a wet year (1985) and a drought year (1988) for the 0–1.0-, 0–0.15-, 0.15–0.5-, 0.5–1.0-, 1.0–2.0-, and 0–2.0-m layers.

Layer (m)	1985				1988			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
0–1.0	370.5	359.3	322.9	328.6	372.3	340.4	239.5	267.3
0–0.15	56.1	49.6	41.5	42.2	55.3	44.5	22.3	34.9
0.15–0.5	127.5	119.2	103.7	106.7	128.3	111.7	67.5	84.9
0.5–1.0	186.9	190.5	177.7	179.7	188.7	184.2	149.7	147.5
1.0–2.0	365.0	374.3	363.1	359.7	361.7	364.6	347.2	333.3
0–2.0	735.5	733.6	686.0	688.3	734.0	705.0	586.7	600.6

layers 1.0–2.0 m occurred during the spring months, declined through the summer and autumn, and recharged during the winter. On average, there was little change in soil moisture in the layer 0.5–1.0 m between summer and autumn (Table 5) with soil moisture recharge beginning in autumn during the wet year (1985) and not until winter during the dry year (1988).

An accurate spatial representation of soil moisture (depth of water, water available for plants, and potential evapotranspiration) is difficult for large areas because it requires incorporation of the boundaries of soil units with different water holding capacities into the map. For example, inclusion of data from the Topeka site characterized by Plainfield loamy sand with low soil moisture content results in a "bull's-eye" in the west-central part of Illinois. All the other ICN sites are characterized by silty loam and silty clay loam soils (Table 2). The area of sandy soil surrounding Topeka is much smaller than the area within the bull's-eye on a contour map of mean soil moisture produced using SURFER® (Golden Software 1988). To avoid this problem, data from the Topeka site were removed from the analysis to more clearly show the spatial variations in soil water that are due to variations in sources and sinks of moisture (Fig. 6). Means for each station displayed in Fig. 6 are pooled over three (for winter), four (for autumn), and six (for spring and summer) observations per season for a period of 10 years.

In the winter and spring there is a latitudinal gradient in soil moisture with the northern soils being drier than the southern soils. This soil moisture gradient roughly corresponds to the precipitation gradient in Illinois (Wendland et al. 1992). During the summer and autumn there is a longitudinal soil moisture gradient in the western portion of the state. The decrease from east to west in soil moisture in western Illinois corresponds with an increase in the depth of loess deposits over the region (Fehrenbacher et al. 1984). The deep loess deposits are associated with a more uneven terrain, which likely causes greater runoff of precipitation during summer and autumn rain storms.

The standard deviation (mm) of moisture in the top 1 m of soil across Illinois and for the northern, central, and southern regions of the state are given for the four seasons of the year in Table 7. Data from the Topeka site were included in this table. Variability of soil moisture throughout the state is relatively low in winter and spring (SD $\approx$ 29 mm) with the highest values occurring in northern Illinois and the lowest values in the central portion of the state. The standard deviation of soil moisture range is 45 and 41 mm for the summer and autumn seasons, respectively. A statistically significant latitudinal gradient exists in soil moisture variability for the 10 summers of record, decreasing from north to south within Illinois. In contrast, the spatial variation in the standard deviation of moisture in the top 1 m of soil is very small for autumn.

TABLE 7. Standard deviation (mm) of moisture in the top 1 m of soil across Illinois and for the northern, central, and southern regions of the state for the seasons of the year. Number of observations given in parentheses.*

Season	North	Central	South	State
Winter	37.45[a]	20.77[b]	35.59[a]	29.13
	(62)	(247)	(166)	(475)
Spring	34.85[a]	25.15[b]	28.90[c]	28.74
	(131)	(782)	(349)	(1262)
Summer	51.97[a]	45.96[b]	40.61[c]	45.01
	(136)	(550)	(365)	(1051)
Autumn	41.67[a]	40.97[a]	41.25[a]	41.13
	(92)	(381)	(258)	(731)
Annual	42.92[a]	36.59[b]	36.77[b]	37.50
	(421)	(1960)	(1138)	(3519)

* Differences between numbers with the same subscript for a season (row) are not statistically significant at $\alpha = 0.05$ (F test).

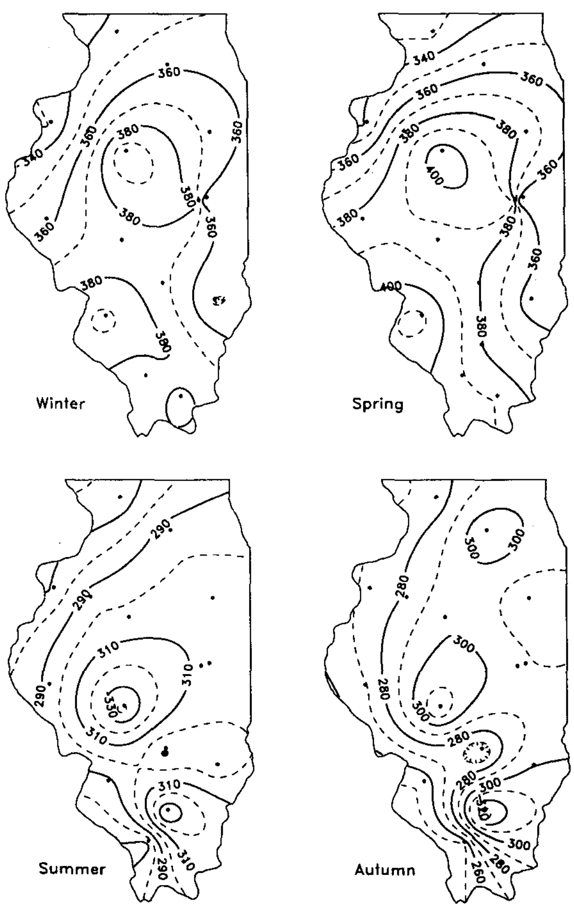

FIG. 6. Spatial variation of the mean soil moisture during each season using the entire record for all stations except Topeka (sandy soil). Maps were produced using SURFER® (Golden Software 1988). Data grids were constructed using the kriging procedure with grid size = 75 and nearest-neighbor search radius = 100 data units.

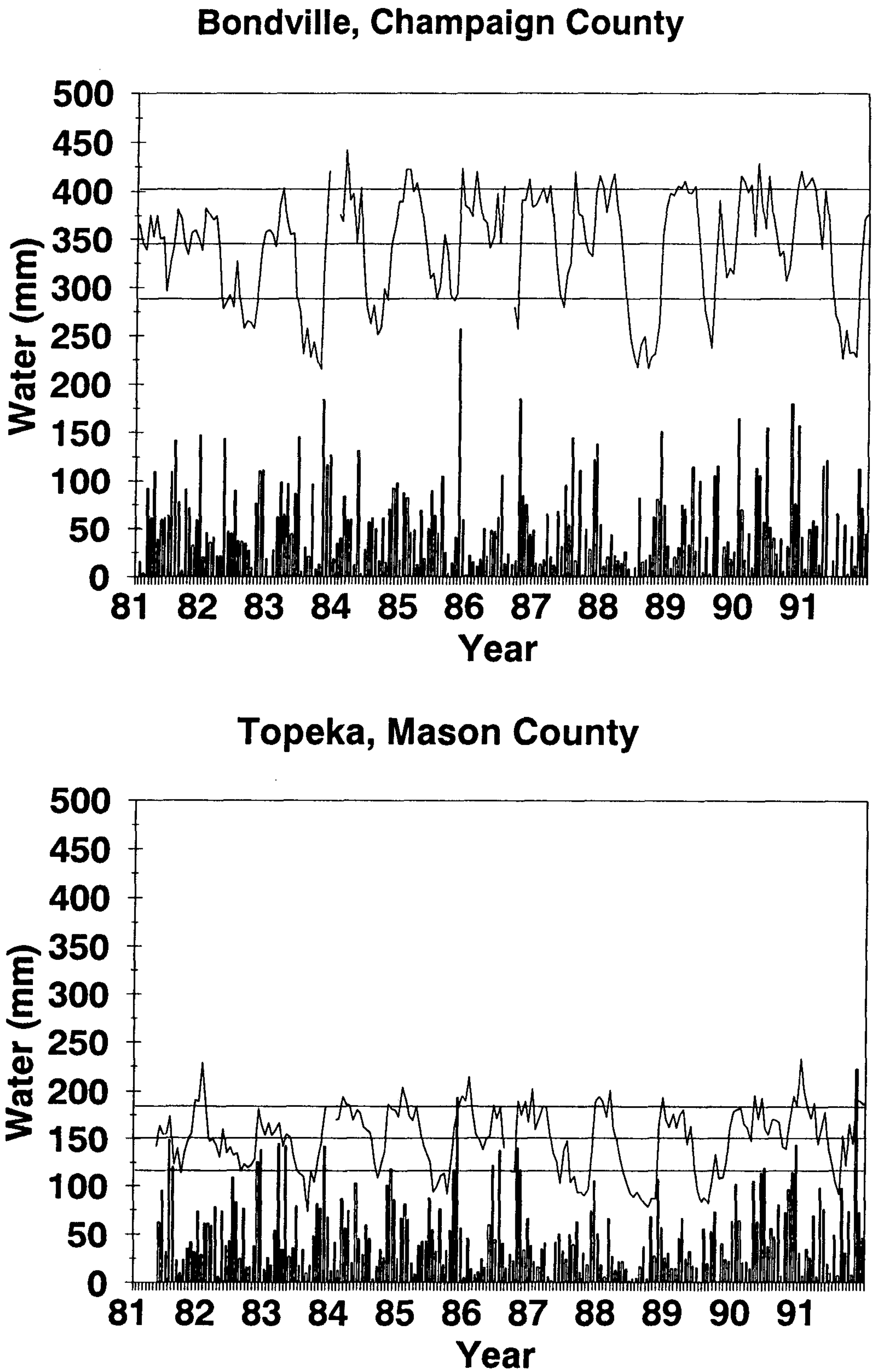

FIG. 7. Time series of soil moisture and precipitation observations for the Topeka (Plainfield loamy sand soil) and Bondville (poorly drained, silt–loam soil) ICN sites.

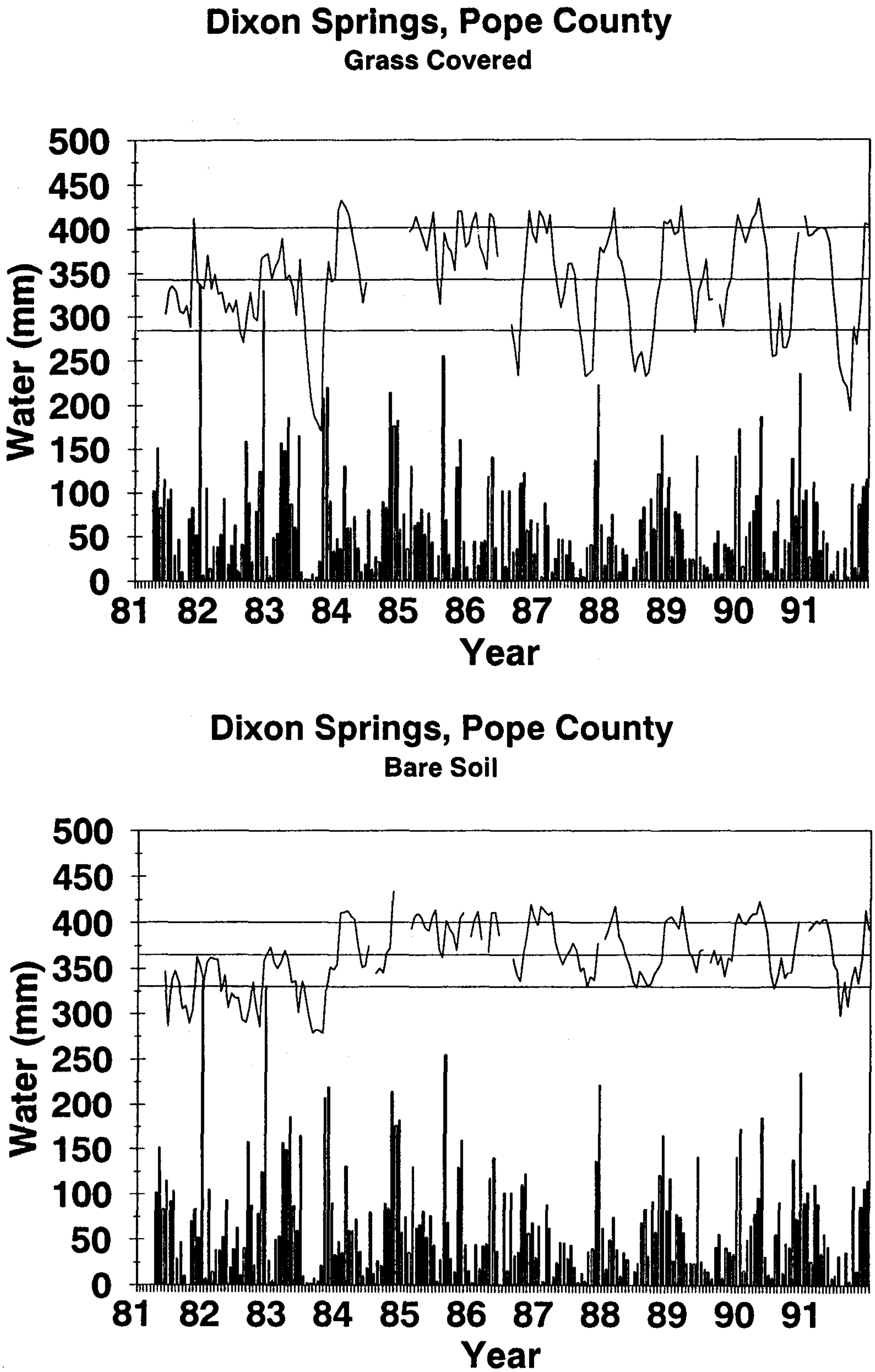

FIG. 8. Time series of soil moisture and precipitation observations for the grass-covered and bare soil sites at Dixon Springs.

As indicated above, the vast majority of soils in Illinois have silt–loam or silt–clay–loam textures. The most noticeable exceptions to this generalization are the soils along the Mississippi, Illinois, and Kankakee Rivers where loamy sands and sands occur. These sandy soils are characterized by very little soil structure, low organic matter, and relatively low porosity. An inspection of Fig. 7 allows comparison between the time series of soil moisture observations in the Plainfield loamy sand soil at Topeka in Mason County, and at Bondville in Champaign County, a site located on a poorly drained, silt–loam soil that is high in organic matter and without a natural dense layer in the top 2 m. Precipitation over the 10-year period at the two sites was similar. However, there was usually twice as much water in the top 1 m of soil at Bondville than at Topeka, most likely due to differences in soil texture and structure, which impact soil water retention. Differences in the response of soil moisture to individual large precipitation events at the two sites, however, are not readily apparent.

Time series of soil moisture and precipitation observations for adjacent grass-covered and bare soil sites at Dixon Springs are presented in Fig. 8. The range in moisture in the top 1 m of soil throughout the year at the vegetated site is 1 to 2 times greater than at the bare soil location. Although total porosity measurements for the two sites were similar, the vegetated site generally contains 50–75 mm more water in the top 1 m of soil during spring when soil moisture is greatest, than does the nonvegetated site. The soil at the nonvegetated site does not dry out as rapidly as the soil at the grass-covered site. As a result, even though soil moisture is greater at the vegetated than bare soil site during spring, desiccation is so much more rapid that there is usually a greater deficit of soil moisture at the vegetated than bare soil site during the summer. Because the deficit in summer is greater, soil moisture at the vegetated site responds more dramatically to summer precipitation events than at the bare site.

4. Summary

Ten years of neutron probe moisture measurements with fine vertical resolution in the top 1 m of the soil are analyzed to provide a climatology of soil moisture for Illinois. Soil moisture profile measurements have been obtained since 1982 at 15 grass-covered sites distributed throughout the state at a biweekly temporal resolution during the growing season and monthly during winter. Currently, there are 17 soil moisture monitoring sites in Illinois.

The neutron probes used to measure the soil moisture were calibrated to each of the stations. Measurement errors at the stations were dependent upon the volumetric soil moisture content of each soil layer. For the top 1 m of soil, measurement errors ranged from 6 percent to 13 percent when volumetric soil moisture was 30 percent of saturation. In Illinois, volumetric soil moisture was typically above 30 percent of saturation for most of the year.

The average depletion of soil moisture between winter and summer in the top 2 m of soil in Illinois is 72.7 mm. Three-quarters of this decrease occurred above 0.5 m and only 5 percent occurred between the 1.0- and 2.0-m depths. The average decrease between winter and summer during a wet year (1985) and a drought year (1988) in the top 2 m was 69 percent and 203 percent, respectively, of the average for the 10-year period. Seventy-eight percent of the decrease in the top 2 m of the soil occurred in the 0–0.5-m layer during the wet year while only 64 percent of the desiccation in the 2-m-deep soil column occurred in the same layer during the 1988 drought year.

Contour maps of mean moisture in the top 1 m of soil for the 10-year record show the spatial variation of soil moisture across the state by season. When data from the sandy soil at Topeka were not included in the analysis, a latitudinal gradient of soil moisture existed during the winter and spring with the wetter soils located in the southern part of the state. During the summer and autumn a decrease from east to west is evident with the drier soils in the western part of the state. The longitudinal gradient of soil moisture corresponds to the depth of loess deposits with the drier soils occurring in the region of the state with deep loess and uneven terrain.

Variations of soil moisture within each season over the 10-yr period were greater in the summer and autumn (SD $\approx$ 41 and 45 mm, respectively) than for winter and spring (SD $\approx$ 29 mm). In general, soil moisture in the northern portion of the state was more variable than in the southern parts of Illinois during spring and summer. The north to south latitudinal gradient of soil moisture variability for the summer season is statistically significant.

Time series of soil moisture and precipitation from sites with silty loam and loamy sand soils indicate the importance of soil texture on soil moisture conditions. Typically there was twice as much water in the top 1 m of the silt loam than loamy sand soil. Finally, time series of soil moisture show that seasonal variation in water in the top 1 m of soil at a grass-covered site was 1 to 2 times greater than at an adjacent nonvegetated site.

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