Prepared in cooperation with the U.S. Department of Agriculture Natural Resources Conservation Service

Water-Balance Techniques for Determining Available Soil-Water Storage for Selected Sandy and Clay Soil Study Sites in Cass County, North Dakota, 2016–17

Scientific Investigations Report 2019–5141

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

Cover. Photograph showing instrument placement at the Embden East study site. Photograph by Kevin Vining, U.S. Geological Survey.

Back Cover. Photograph showing instrument placement at the Brewer Lake study site. Photograph by Kelsey Kolars, U.S. Geological Survey.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.0929	square meter (m^2)
acre	0.405	hectare (ha)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Energy	
calorie (cal)	4.19	Joule (J)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F–32)/1.8.$$

Temperature in degrees Kelvin (K) may be converted to °C as follows:

$$°C=K–273.15$$

Supplemental Information

Soil dry bulk density is given in grams of dry soil per cubic centimeter of soil volume.

Soil gravimetric water content is given in grams of water lost by drying per grams of dry soil, or percent. Soil volumetric water content is given in cubic centimeters per cubic centimeter.

Density of water is given in grams per cubic centimeter. Density of air is given in kilograms per cubic meter.

Horizontal spatial resolutions, or pixel sizes, are given in kilometers.

Net radiation is given in Joules per square meter per second.

Aerodynamic resistance is given in seconds per meter.

Specific heat of air at constant pressure is assumed to be 1.013 kiloJoules per kilogram per degree Kelvin.

Datum

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

Abbreviations

AWS	available soil-water storage
ET	evapotranspiration
MODIS	Moderate Resolution Imaging Spectroradiometer
NDAWN	North Dakota Agricultural Weather Network
NRCS	Natural Resources Conservation Service
PET	potential evapotranspiration
SSEBop	Operational Simplified Surface Energy Balance
SWE	snow water equivalent
USGS	U.S. Geological Survey

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By Kevin C. Vining

Abstract

The U.S. Geological Survey, in cooperation with the U.S. Department of Agriculture Natural Resources Conservation Service, collected field and remotely sensed data on precipitation, evapotranspiration (ET), and soil-water content to determine available soil-water storage (AWS) at six study sites on sandy and clay soils in Cass County, North Dakota. Data were collected at all the study sites from May 1–October 31, 2016, and from May 1–October 24, 2017. Estimated daily AWS was determined using daily meteorological and potential evapotranspiration (PET) data obtained from various climate stations, and estimated monthly AWS was determined using monthly meteorological and PET data and monthly ET data determined using the Operational Simplified Surface Energy Balance model. AWS during 2016 and 2017 was determined at daily and monthly time steps because of data availability and to assess results using varying time steps. Comparisons of measured and estimated daily values of AWS at the Brewer Lake site indicated poor agreement during May–October 2016 and May–October 2017. Comparisons of measured and estimated daily values of AWS at the Embden East and Embden West sites indicated poor and fair agreement, respectively. At the Lynchburg Crop and Lynchburg Grass sites, comparisons of measured and estimated daily values of AWS indicated fair and good relations, respectively, even with the possible effects of soil cracks. Mean estimated values of daily runoff plus soil percolation for the four sandy soil sites indicated that a maximum of about 19 percent of the estimated runoff plus soil percolation could be considered runoff and that the remaining 81 percent could be considered soil percolation, and for the two clay soil sites about 13 percent of the runoff plus soil percolation could have been considered runoff and about 87 percent could have been considered soil percolation. Results indicated little difference between using monthly PET or monthly ET in water-balance equations to estimate monthly AWS for the grouped sandy soil sites, and only slightly better results were obtained using monthly PET than monthly ET to estimate monthly AWS for the grouped clay soil study sites. Overall, the monthly water-balance models did not perform as well as the daily water-balance models for determining AWS at the six study sites. Additional data collection from a longer-period study and adjustments to the models may improve results from the monthly water-balance techniques.

Introduction

Soil water has been difficult to manage agriculturally in Cass County, North Dakota, especially in the low-relief silty and clay soils of the county. Excess soil water, runoff, and extensive flooding often occur during spring because of snowmelt on frozen soil coupled with occasional large amounts of rainfall. Noteworthy examples of large floods in the Red River of the North Basin occurred in 1997, 2009, and 2011 (U.S. Geological Survey, 2019). During similar wet periods, agricultural producers can experience long delays until soils are trafficable leading to potential reductions in crop productivity. Drainage techniques for removing soil water quickly, such as placing a network of perforated plastic pipes (tiles) into the top few feet of agricultural fields and digging surface ditches into fields, can be used to divert water to nearby waterways to hasten drying of fields, but these activities can introduce or exacerbate flooding in downstream areas.

The Natural Resources Conservation Service (NRCS), a branch of the U.S. Department of Agriculture, “uses science-based technology to provide conservation planning and assistance to land owners and operators and others to benefit the soil, water, air, plants, and animals for productive lands and healthy ecosystems” (U.S. Department of Agriculture, 2019). In 2011, the NRCS started the Red River Basin Initiative, which includes parts of Minnesota, North Dakota, and South Dakota (U.S. Department of Agriculture, 2017). The initiative supplies technical and financial assistance to agricultural producers for reducing soil erosion, improving water quality, and storing water on private lands during flooding. Through other partners, the NRCS also supports the use of field measurements and remote-sensing techniques to evaluate soil-water changes throughout the growing season and estimate water-holding capacity of soils before runoff.

The NRCS works with local, State, and Federal groups to develop conservation strategies, and has a commitment to increase temporary flood storage in the Red River Basin. The U.S. Geological Survey (USGS), in cooperation with the NRCS, collected field and remotely sensed precipitation, evapotranspiration, and soil-water content data on crop-production lands and nearby undisturbed grasslands to determine available soil-water storage (AWS) using water-balance techniques at six study sites on sandy and clay soil types in Cass County, North Dakota to help inform conservation strategies. A basic water-balance technique (water input minus water output equals change in water content) was used at each study site to estimate changes in AWS, which is defined as the quantity of water that a soil can retain in open pores between the limits of permanent wilting point, which is soil-water content at which a plant cannot remain turgid, and field capacity, which is soil-water content after a few days of drainage after saturation (Ward and Trimble, 2004). AWS also is referred to as plant available water. Water placed onto a soil that exceeds AWS would saturate the soil and cause ponding on the soil surface until additional storage volume became available through soil percolation, runoff, or evapotranspiration. An objective of this study was to provide information on AWS determined using water-balance techniques and the potential effect of AWS on runoff that may be used by the NRCS to develop programs to retain water in soils.

Purpose and Scope

The purpose of this report is to present methods and results to determine AWS from field measurements and water-balance techniques at six study sites with sandy and clay soils in Cass County, North Dakota, during 2016–17. These results can provide guidance for estimating AWS over extended areas with sandy and clay soils that are similar to the study sites. Data generated during this study are available as a USGS data release (Vining, 2020).

Descriptions of the Study Sites

The six study sites were selected to represent a range of soil types in Cass County, N. Dak. (fig. 1). Loamy to sandy soils are mostly in the western part of the county, and clay soils are in the central part of the county (table 1; Prochnow and others, 1985). Topography of the six study sites is level to slightly rolling. The climate of the study sites is continental with cold, snowy winters and warm, semihumid summers. About 75 percent of the annual precipitation falls during May–October as shown by data from Fargo, N. Dak. (table 2; National Centers for Environmental Information, 2017).

Sandy Soil Study Sites

A grouping of the Brewer Lake, Embden East, Embden West, and Wills study sites were defined as sandy soil study sites. The Brewer Lake study site was on the Erie Dam/Brewer Lake Wildlife Management Area, the Wills study site was on the Hamilton Wills Wildlife Management Area, and the Embden East and Embden West study sites were on private property (fig. 1). Soils at the Brewer Lake site were classified as loam with sand contents of about 40 to 45 percent and clay contents of about 12 to 24 percent (U.S. Department of Agriculture, 2018). Soils at the Embden East, Embden West, and Wills sites were classified as sandy loam with sand contents of about 70 to 72 percent and clay contents of about 12 to 14 percent (U.S. Department of Agriculture, 2018). Soils at these sites were in the Barnes-Heimdal-Emrick and Embden-Glyndon-Egeland soil associations that are present mostly on glacial plains in western Cass County (Prochnow and others, 1985). These soils are reported to have good drainage and plant-available water capacities of about 13 to 21 percent by volume (U.S. Department of Agriculture, 2018). The Brewer Lake and Wills sites were on undisturbed grasslands that had

Table 1. Descriptions of the six study sites in Cass County, North Dakota.

[NA, not applicable]

Study site (fig. 1)	Latitude, in decimal degrees	Longitude, in decimal degrees	Soil texture	Primary land cover	Tillage practices
Brewer Lake	47.094	−97.429	Sand	Grass	NA
Embden East	46.687	−97.431	Loamy sand	Wheat—2016 Corn—2017	Minimum tillage.
Embden West	46.687	−97.437	Sandy loam	Wheat—2016 Corn—2017	Minimum tillage, subsurface tile drainage.
Lynchburg Crop	46.788	−97.273	Clay	Sugar beets—2016 Soybeans—2017	Standard tillage.
Lynchburg Grass	46.789	−97.273	Clay	Grass	NA
Wills	46.699	−97.409	Loamy sand	Grass	NA

Table 2. Mean monthly and annual climate data for 1981–2010 for Fargo, North Dakota (National Centers for Environmental Information, 2017).

Month	Mean maximum temperature, in degrees Fahrenheit	Mean minimum temperature, in degrees Fahrenheit	Mean precipitation, in inches	Mean snowfall, in inches
January	18.4	0.1	0.70	11.2
February	23.7	5.6	0.61	7.0
March	36.3	19.4	1.30	9.1
April	55.8	32.7	1.36	3.0
May	69.3	44.9	2.81	0.0
June	77.4	54.9	3.90	0.0
July	82.5	59.5	2.79	0.0
August	81.2	57.3	2.56	0.0
September	70.8	47.4	2.57	0.0
October	56.0	35.1	2.15	0.7
November	37.3	20.3	1.00	7.9
December	22.3	5.9	0.83	11.2
Annual	52.7	32.0	22.58	50.1

a variety of grasses and some broadleaf plants. The Embden East and Embden West sites were on continuous production lands where wheat and corn were grown (table 1).

Clay Soil Study Sites

A grouping of the Lynchburg Crop and Lynchburg Grass study sites were defined as clay soil study sites and were on private property (fig. 1). Soils at these sites were clay and in the Fargo-Hegne soil association that are present mostly on glacial lake plains in central Cass County (Prochnow and others, 1985). These soils have clay contents of about 50 percent and sand contents of about 10 percent (U.S. Department of Agriculture, 2018). These soils are reported to have poor drainage and plant-available water capacities of about 14 to 16 percent by volume (U.S. Department of Agriculture, 2018). The Lynchburg Grass site was on undisturbed grasslands, and the Lynchburg Crop site was on continuous production lands where sugar beets and soybeans were grown (table 1).

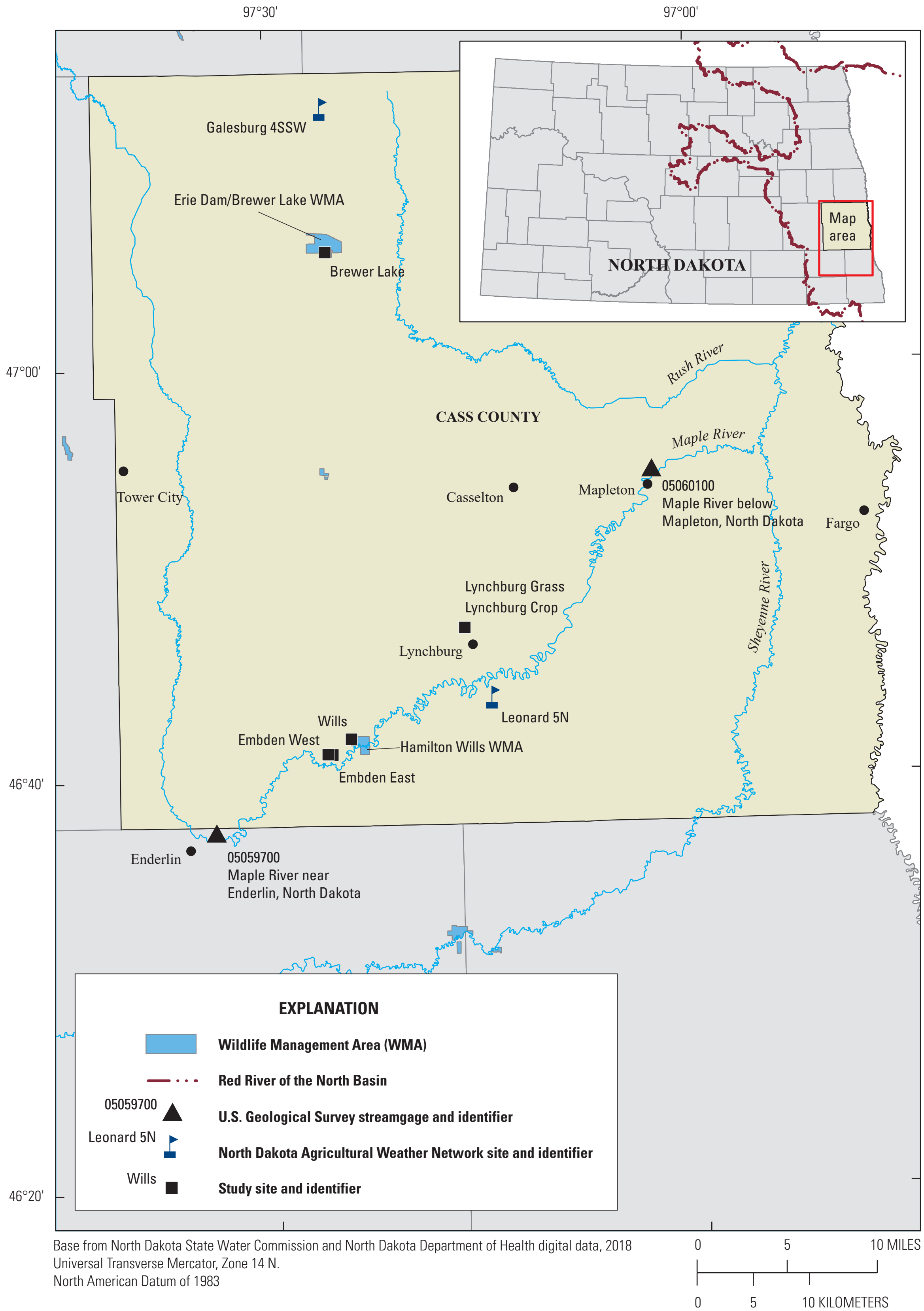


Figure 1. Locations of the six study sites in Cass County, North Dakota.

Methods

Data collected at the study sites included soil volumetric water-content data and soil physical data. Other relevant data were obtained from readily available climate sources and through remote-sensing techniques. The data provided input and comparative information for water-balance techniques that were used to determine AWS at the study sites and for basic regression analyses at the study sites.

AWS is directly related to the soil physical properties at each study sites, which can affect the installation of soil volumetric water-content probes and measurements of soil volumetric water-content data. The methods and ease of collecting soil samples for determining soil gravimetric water content, soil dry bulk density, and soil volumetric water content could also be affected by soil physical properties. In addition, the published values of soil volumetric water content at field capacity and permanent wilting point, which were used for AWS determination, were mean values for the various soil types. Soils are rarely homogeneous, and actual field capacity and permanent wilting point volumetric water contents often vary horizontally depending on soil properties (Ward and Trimble, 2004).

Data Collection and Sources

Data collection consisted primarily of soil volumetric water-content data at all six study sites (fig. 2). Data collection was hourly during May 1–June 16, 2016, and then every 15 minutes during June 17–October 31, 2016, and May 1–October 24, 2017, at all sites. Soil volumetric water-content data were reported as daily values using the last reading of each day. Data generated during this study are available as a USGS data release (Vining, 2020).

Precipitation data used for the study sites (fig. 3) were obtained from the North Dakota Agricultural Weather Network (NDAWN) stations near Galesburg, N. Dak., and Leonard, N. Dak. (North Dakota State University, 2017; fig. 1). Precipitation data from the Galesburg station were considered representative for the Brewer Lake site, and data from the Leonard station were considered representative for the Embden East site, the Embden West site, the Lynchburg Crop site, the Lynchburg Grass site, and the Wills site. The NDAWN precipitation gages were calibrated according to NDAWN maintenance guidelines and schedules (North Dakota State University, 2019).

At each of the six sites, soil volumetric water-content data (as a percentage of soil volume) were collected from four 1-foot soil volumetric water-content probes placed in the soil,

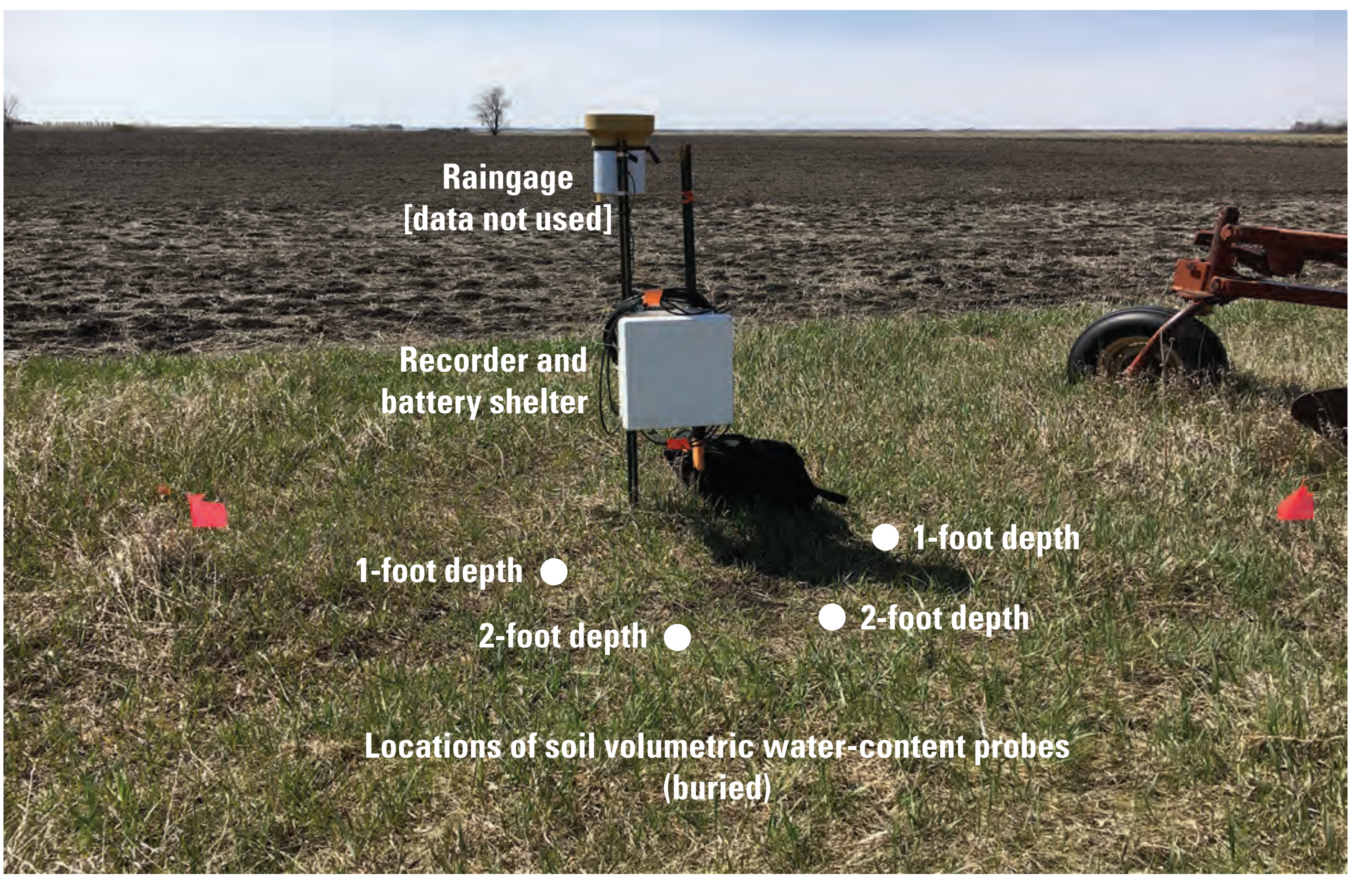


Figure 2. An example instrument placement used at the six study sites in Cass County, North Dakota.

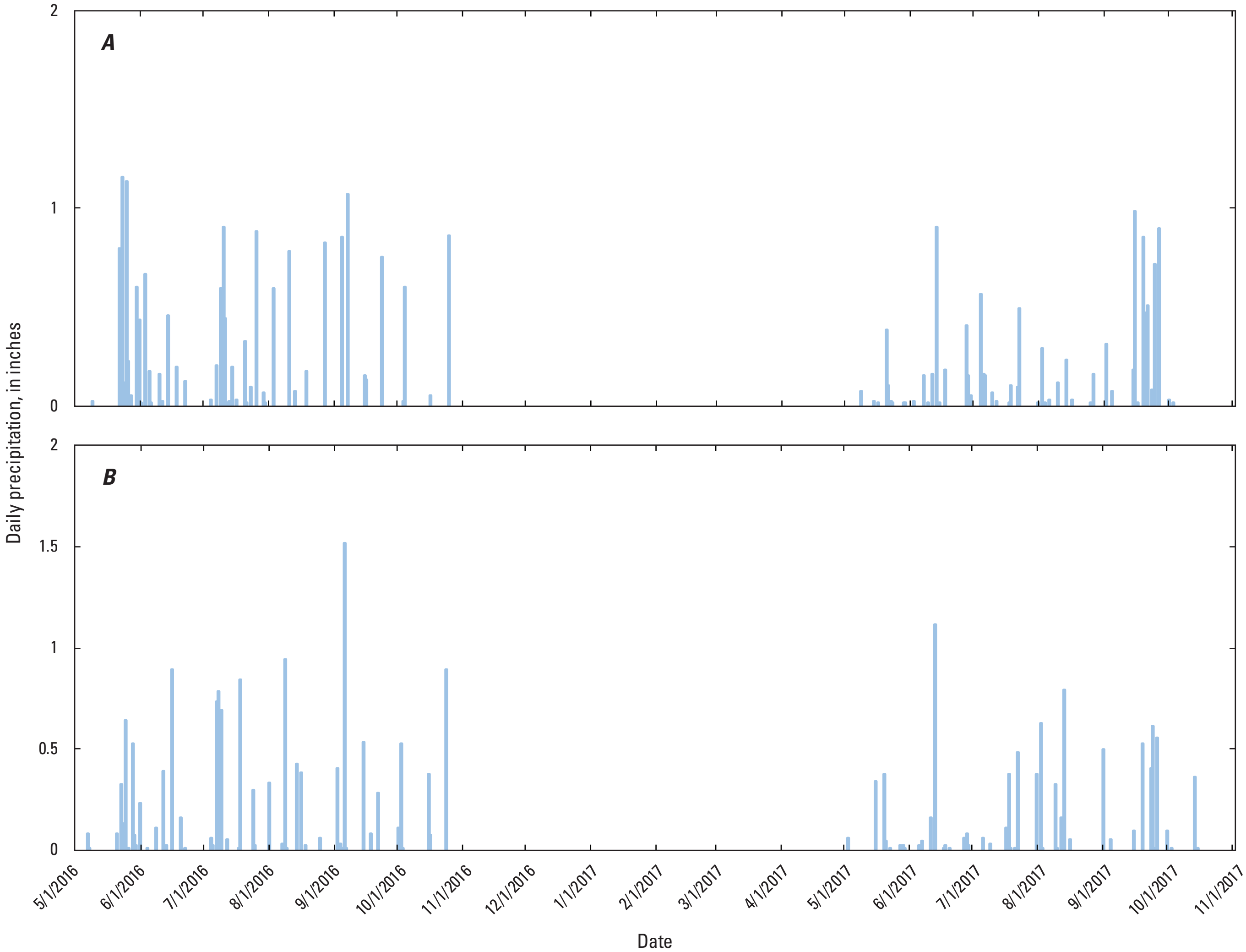


Figure 3. Daily precipitation from May to October in 2016 and 2017 for the two North Dakota Agricultural Weather Network stations used for the study sites in Cass County, North Dakota. *A*, Galesburg, North Dakota, station, *B*, Leonard, N. Dak., station.

two at the 0- to 1-foot depth interval and two at the 1- to 2-foot depth interval beneath the ground surface to have a replicate at each depth in case of probe failure. The probes were installed in an east to west orientation at five of the six sites (fig. 2). Probes at the Wills site were installed in a north to south orientation. Values from the two probes at each depth interval were averaged to provide one soil volumetric water-content value for each depth interval. Past studies indicate that soil volumetric water-content probes function better in coarse-textured sandy soils than in fine-textured clay soils (University of California, Davis, 2017). Soils with clay contents greater than about 50 percent have been reported to cause underestimation of water content in drier soil conditions and overestimation of water content in wetter soil conditions using soil volumetric water-content probes (Gong and others, 2003).

Soil samples were collected several times during each growing season to determine soil gravimetric water content and soil dry bulk density (table 3) and for calibrating soil volumetric water-content probe data. Soil samples of known volume were weighed in cans of known mass by USGS personnel and then dried for 24 hours at 104 degrees Celsius at a U.S. Department of Agriculture Agricultural Research Service laboratory following procedures in Klute (1986). After drying, samples were weighed to determine soil dry bulk density (grams of dry soil per cubic centimeter of soil volume) and to determine soil gravimetric water content (grams of water lost by drying per gram of dry soil). Volumetric water contents of the soil samples were determined as the product of soil gravimetric water content and soil dry bulk density using equation 1 (Hillel, 1980):

$$\theta v = \theta g \times \rho b / \rho w \quad (1)$$

where

θv is soil volumetric water content, in cubic centimeters per cubic centimeter,

Table 3. Gravimetric water content and dry bulk density obtained from soil samples collected at the six study sites in Cass County, North Dakota.

[Water content is given in grams per gram. Bulk density is given in grams per cubic centimeter. NA, not applicable]

Date	Soil depth interval, in feet	Study sites (fig. 1)											
		Brewer Lake		Embden East		Embden West		Lynchburg Crop		Lynchburg Grass		Wills	
		Water content	Bulk density	Water content	Bulk density	Water content	Bulk density	Water content	Bulk density	Water content	Bulk density	Water content	Bulk density
June 2, 2016	0–1	0.12	1.42	0.11	1.41	0.16	1.39	0.42	1.22	0.32	1.14	0.17	1.62
	1–2	0.11	1.78	0.10	1.54	0.16	1.83	0.41	1.25	0.38	1.22	0.18	1.51
June 27, 2016	0–1	0.06	1.28	0.05	1.42	0.12	1.70	0.41	1.12	0.33	1.00	0.13	1.37
	1–2	0.06	1.46	0.05	1.41	0.17	1.66	0.40	1.34	0.33	1.27	0.16	1.44
August 1, 2016	0–1	0.08	1.41	0.07	1.39	0.14	1.92	0.30	1.32	0.39	1.11	0.09	1.44
	1–2	0.07	1.37	0.09	1.66	0.14	1.64	0.30	1.22	0.30	1.16	0.16	1.60
October 13, 2016	0–1	0.11	1.39	0.08	1.36	0.14	1.63	0.35	1.18	0.44	1.11	0.15	1.47
	1–2	0.09	1.22	NA	NA	0.15	1.69	0.31	1.24	0.37	1.23	0.16	1.57
November 7, 2016	0–1	0.12	1.36	0.11	1.62	0.15	1.63	0.41	1.23	0.44	1.25	0.15	1.71
	1–2	0.10	1.44	0.11	1.54	0.16	1.54	0.37	1.29	0.40	1.20	0.15	1.67
August 31, 2017	0–1	0.09	1.35	0.07	NA	0.11	NA	0.29	1.14	0.29	1.21	0.17	NA
	1–2	0.08	1.39	NA	NA	0.10	NA	0.31	1.46	0.28	0.98	0.15	NA
October 12, 2017	0–1	0.10	1.45	0.11	1.52	0.16	1.71	0.42	1.19	0.38	1.11	0.19	1.37
	1–2	0.09	1.36	0.15	1.49	0.16	1.58	0.36	1.04	0.33	1.16	0.16	1.54
October 25, 2017	0–1	0.09	1.41	0.11	1.49	0.17	1.56	0.38	1.07	0.43	1.06	0.17	1.44
	1–2	0.08	1.49	0.12	1.49	0.16	1.74	0.32	1.13	0.40	1.18	0.15	1.64
Average soil dry bulk density	0–1	NA	1.38	NA	1.46	NA	1.65	NA	1.18	NA	1.12	NA	1.49
	1–2	NA	1.44	NA	1.52	NA	1.67	NA	1.25	NA	1.18	NA	1.57
[1]Web Soil Survey values of soil dry bulk density	0–1	NA	1.38	NA	1.30	NA	1.30	NA	1.23	NA	1.23	NA	1.39
	1–2	NA	1.43	NA	1.42	NA	1.42	NA	1.24	NA	1.24	NA	1.48

[1]U.S. Department of Agriculture (2018).

or percent;

θg is soil gravimetric water content, in grams per gram, or percent;

ρb is soil dry bulk density, in grams per cubic centimeter; and

ρw is density of water, in grams per cubic centimeter (assumed to be 1.0).

Complete procedures for determining soil gravimetric water content and soil dry bulk density are provided in Klute (1986). Calibration analyses were made between soil-sample volumetric water-content values (table 3) and soil volumetric water-content data that were measured using the soil volumetric water-content probes at each study site. The resulting analyses were used to calibrate the values measured using the probes (table 4; Vining, 2020).

Daily values of potential evapotranspiration (PET), calculated using the Penman method (Penman, 1948), were obtained from the NDAWN stations at Galesburg, N. Dak., and Leonard, N. Dak. (North Dakota State University, 2017). PET is defined as the amount of evapotranspiration (ET) that would occur from a surface during a period if water supply is unlimited (Ward and Trimble, 2004) and essentially represents the upper limit of ET for a set of environmental conditions when sufficient water is available. Often, the reference surface for PET is an area of well-watered short grass. ET is the actual amount of water loss from the land surface and plants for a given set of environmental, soil, and plant conditions and is difficult to determine accurately without complex instrumentation (Rosenberg and others, 1983).

Piezometers were installed to a depth of 3 feet at the Brewer Lake, Embden East, Lynchburg Crop, and Wills sites during June 2016 to measure shallow groundwater levels during site visits. No water was detected in any of the bore holes during installation; therefore, it was unlikely that shallow groundwater would affect soil volumetric water contents at any of the study sites.

Snow water equivalents (SWEs) for the six study sites were estimated from airborne surveys by the National Operational Hydrologic Remote Sensing Center at the National Weather Service in Chanhassen, Minnesota (National Weather Service, 2018). SWE data indicated near-maximum values of about 1.5 inches near the Brewer Lake, Embden East, Embden West, and Wills sites and about 0.5 inch near the Lynchburg Crop and Lynchburg Grass sites on February 10, 2017 (National Weather Service, 2018). Snow cover at all sites was mostly melted by March 20, 2017. SWE was not included in the water-balance analyses at the study sites because of the small amounts of SWE that occurred during winter 2016–17.

Monthly precipitation and monthly PET data that were used to estimate monthly AWS were obtained from the NDAWN stations at Galesburg, N. Dak., and Leonard, N. Dak. Monthly ET was estimated by the USGS Earth Resources Observation and Science Center using the Operational Simplified Surface Energy Balance model (SSEBop; Senay and others, 2013).

Determining Monthly Evapotranspiration Using the Operational Simplified Surface Energy Balance Model

Monthly totals of ET were estimated using satellite remote-sensing techniques and the SSEBop model (Senay and others, 2013). SSEBop is a robust method that uses remotely sensed thermal data and weather information to produce ET estimates for the contiguous United States at monthly and seasonal time scales.

Two satellite data sources, Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS), were used for SSEBop development (Senay and others, 2013). Landsat and MODIS have horizontal spatial resolutions, or pixel sizes, of about 0.1 and 1 kilometer, respectively, and temporal resolutions of 16 and 8 days, respectively. To minimize the mixing of information within a pixel image, areas of interest should be about the size of the spatial resolution of the image. In the case of mixed cover types in a pixel, area-weighted parameters must be derived to characterize physical processes. MODIS data were used with Landsat data because the 8-day resolution is appropriate for many agricultural and hydrological applications, and the data can be used to fill cloudy Landsat pixels to

Table 4. Calibration equations to calculate adjusted soil volumetric water contents from values measured using the soil volumetric water-content probes at the six study sites in Cass County, North Dakota.

[*y*, adjusted soil volumetric water contents; *x*, soil volumetric water contents measured using the soil volumetric water content probes]

Study site (fig. 1)	Calibration equation	
	0- to 1-foot depth interval	1- to 2-foot depth interval
Brewer Lake	$y=(0.689)x$	$y=(0.831)x$
Embden East	$y=(0.779)x$	$y=(0.766)x$
Embden West	$y=(0.656)x$	$y=(0.649)x$
Lynchburg Crop	$y=(0.723)x$	$y=(0.763)x$
Lynchburg Grass	$y=(0.650)x$	$y=(0.512)x$
Wills	$y=(0.717)x$	$y=(0.762)x$

generate an ET time series (Senay and others, 2013). The 8- to 16-day satellite temporal resolution limited the generation of satellite-derived ET values to a monthly time step only.

The SSEBop model defines limiting conditions based on clear-sky net radiation balance principles and predefines "hot/dry" and "cold/wet" limiting temperatures for each satellite pixel (Senay and others, 2013). To estimate ET routinely, the only data needed for the SSEBop method are surface temperature, air temperature, and PET. The ET for a pixel location can then be estimated as a fraction of PET using equation 2 (Senay and others, 2013):

$$ET = ETf \times k \times ETo \qquad (2)$$

where

ETo is PET for the location, in inches;

k is a coefficient that scales *ETo* to the level of a maximum ET for various vegetation types; and

ETf is an ET fraction, in percent, determined by equation 3:

$$ETf = \frac{Th - Ts}{dT} = \frac{Th - Ts}{Th - Tc} \qquad (3)$$

where

Ts is the satellite-observed land surface temperature of the pixel location at a known time for which *ETf* is being evaluated, in degrees Kelvin;

Th is the estimated *Ts* at the idealized "hot/dry" temperature limit of the same pixel location for the same time, in degrees Kelvin;

Tc is the estimated *Ts* at the idealized "cold/wet" temperature limit of the same pixel location for the same time, in degrees Kelvin; and

dT is a pre-defined temperature difference between *Th* and *Tc* determined during the peak crop growing season (Senay and others, 2013), in degrees Kelvin.

Tc was calculated at each pixel as the air temperature (*Ta*) obtained from the Parameter-elevation Regressions on Independent Slopes Model (called "PRISM"; Northwest Alliance for Computational Science and Engineering, 2018) multiplied by a correction coefficient (*c*) that was defined as the growing-season mean of the values of *Tc* and *Ta* that were determined on satellite flyovers for surrounding well-watered and fully vegetated pixels during the growing season. The equation for *Tc* is equation 4 (Senay and others, 2013):

$$Tc = c \times Ta \qquad (4)$$

Th was then determined as the sum of *Tc* and *dT*. The value of *dT* is assumed to be unique for each day and location and is calculated using equation 5 using the assumptions of a clear-sky and little change in value from year to year (Senay and others, 2013):

$$dT = (R_n \times r_{ah}) \div (\rho_a \times C_p) \qquad (5)$$

where

R_n is daily mean clear-sky net radiation, in Joules per square meter per second, calculated using available data (Allen and others, 1998);

r_{ah} is the aerodynamic resistance to heat transfer from a hypothetical bare and dry surface, assumed to be 110 seconds per meter (Senay and others, 2013);

ρ_a is the density of air, in kilograms per cubic meter, estimated as a function of air pressure and air temperature (Allen and others, 1998); and

C_p is the specific heat of air at constant pressure, assumed to be 1.013 kiloJoules per kilogram per degree Kelvin.

Then, with algebraic rearrangement of equations 2–5, ET can be calculated using equation 6 (Senay and others, 2013):

$$ET = ([\rho_a \times C_p] \div [R_n \times r_{ah}]) \times (Th - Ts) \times k \times ETo \qquad (6)$$

Estimated monthly ET derived from the SSEBop model for the 2016 and 2017 growing seasons in Cass County are shown in figures 4 and 5, respectively (Senay and others, 2017). Monthly ET totals during May and October were the least of any month across the county for the period May–October 2016 and 2017 as shown by the lighter coloration on the figures. Crop growth during May often just starts with many fields nearly bare, and October crop growth is often finished for a growing season. If the soil surface is bare, dry, and warm, monthly ET could be small even if soil moisture remains abundant below the surface (Ward and Trimble, 2004). The areas just northwest of the Embden and Wills sites indicated greater amounts of ET during most months (darker shades) reflecting the presence of numerous small lakes and wetlands. In general, monthly ET for Cass County reached maximum values during July and August 2016 and 2017.

Determining Daily and Monthly Available Soil-Water Storage and Daily Runoff Plus Soil Percolation

AWS during 2016 and 2017 was determined at daily and monthly time steps because of data availability and to assess results using varying time steps. Two values for daily and monthly AWS were determined, referred to as "measured" and "estimated" values. Measured daily AWS was

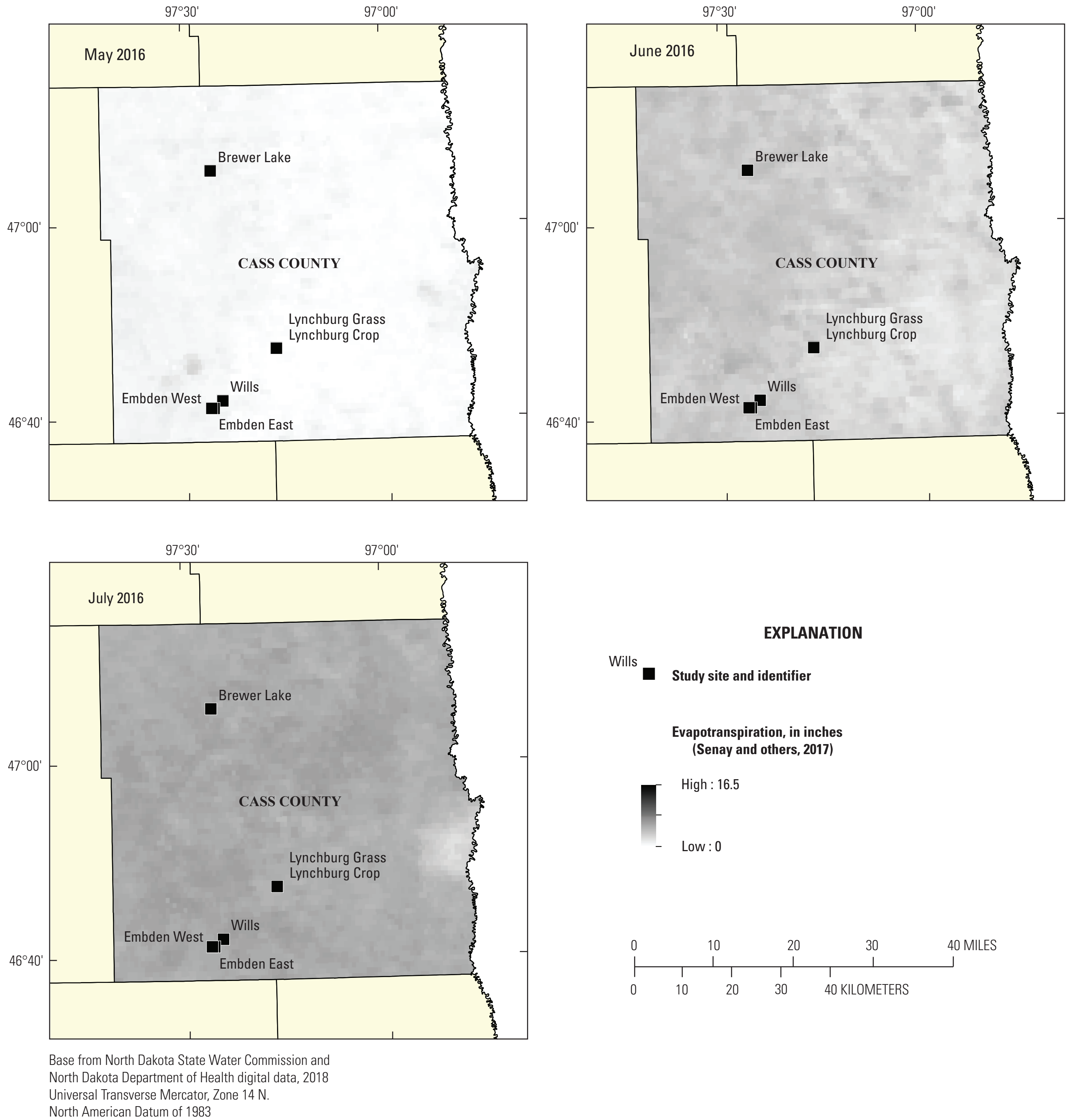
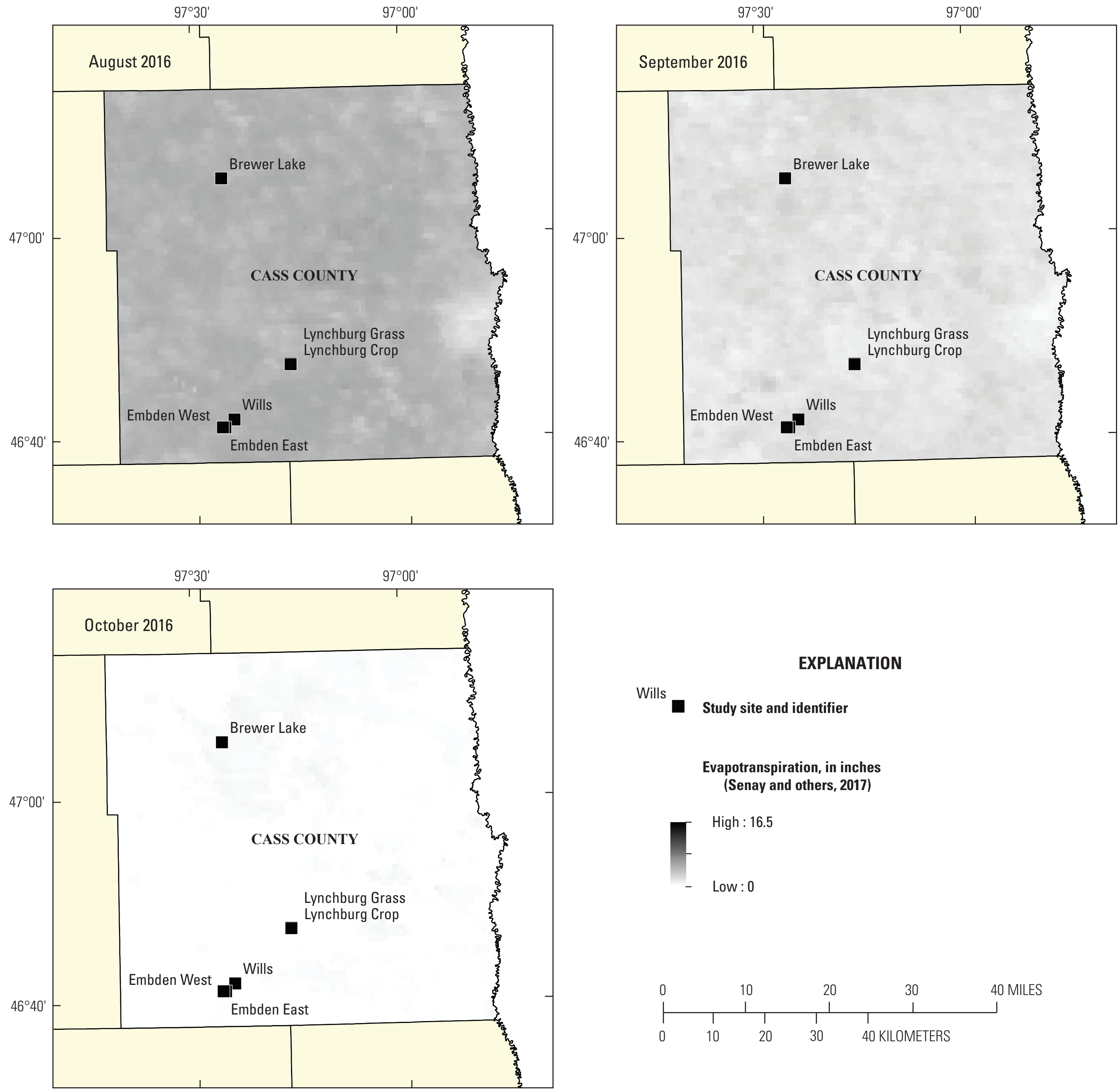


Figure 4. Estimated monthly evapotranspiration for May–October 2016 for Cass County, North Dakota, derived from the Operational Simplified Surface Energy Balance model.

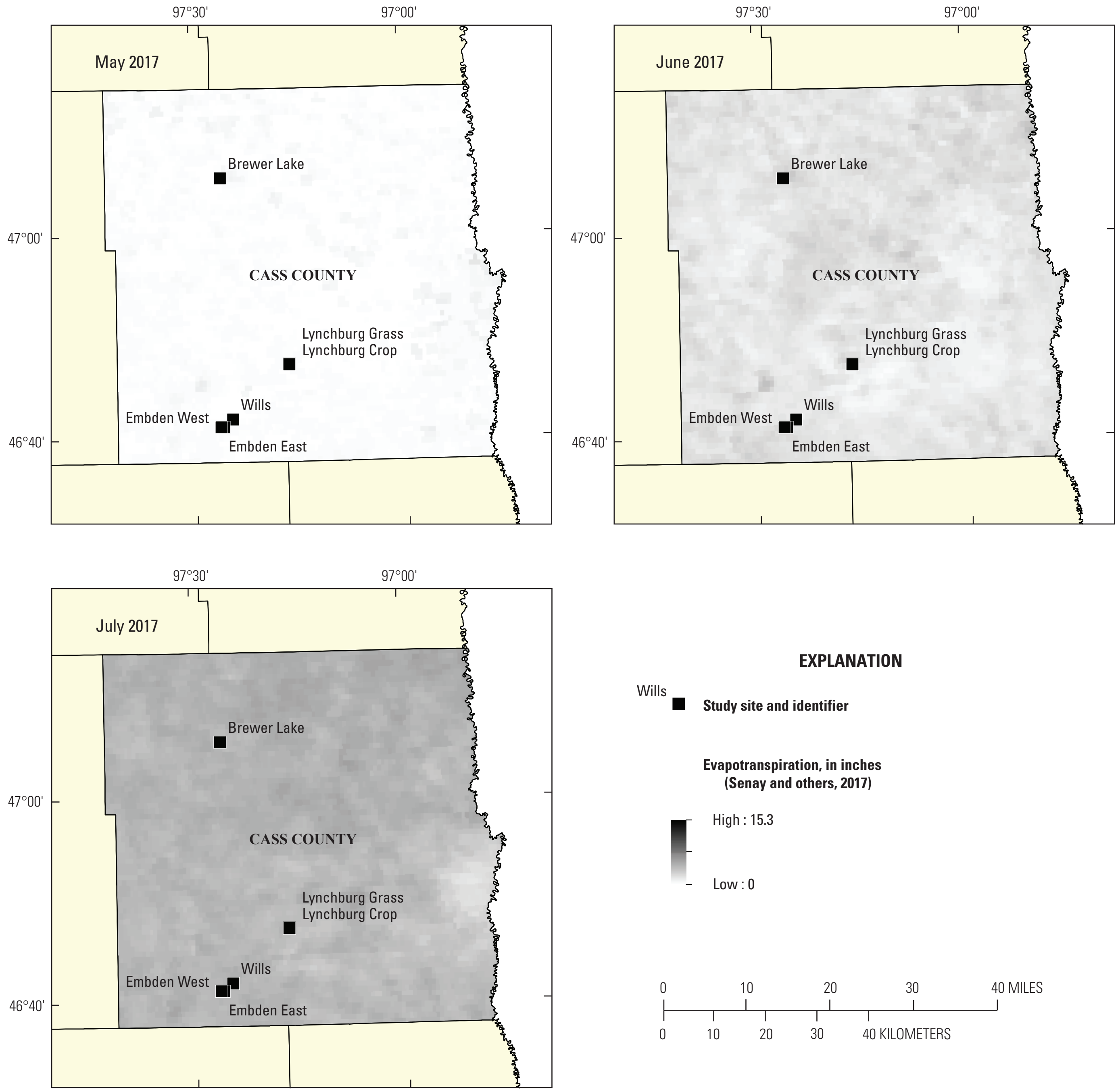
determined from daily soil volumetric water-content data and other soil physical data from the study sites. Estimated daily AWS was calculated from daily precipitation and PET data from the study sites and nearby climate stations that were used in water-balance equations. Measured monthly AWS was determined from aggregated daily soil volumetric water content. Estimated monthly AWS was calculated using two methods, the first using precipitation and PET data from the study sites and nearby climate stations, and the second using



Base from North Dakota State Water Commission and
North Dakota Department of Health digital data, 2018
Universal Transverse Mercator, Zone 14 N.
North American Datum of 1983

Figure 4. Estimated monthly evapotranspiration for May–October 2016 for Cass County, North Dakota, derived from the Operational Simplified Surface Energy Balance model.—Continued

precipitation from the study sites and nearby climate stations and monthly SSEBop ET data. Methods for determining AWS are described herein.



Base from North Dakota State Water Commission and
North Dakota Department of Health digital data, 2018
Universal Transverse Mercator, Zone 14 N.
North American Datum of 1983

Figure 5. Estimated monthly evapotranspiration for May–October 2017 for Cass County, North Dakota, derived from the Operational Simplified Surface Energy Balance model.

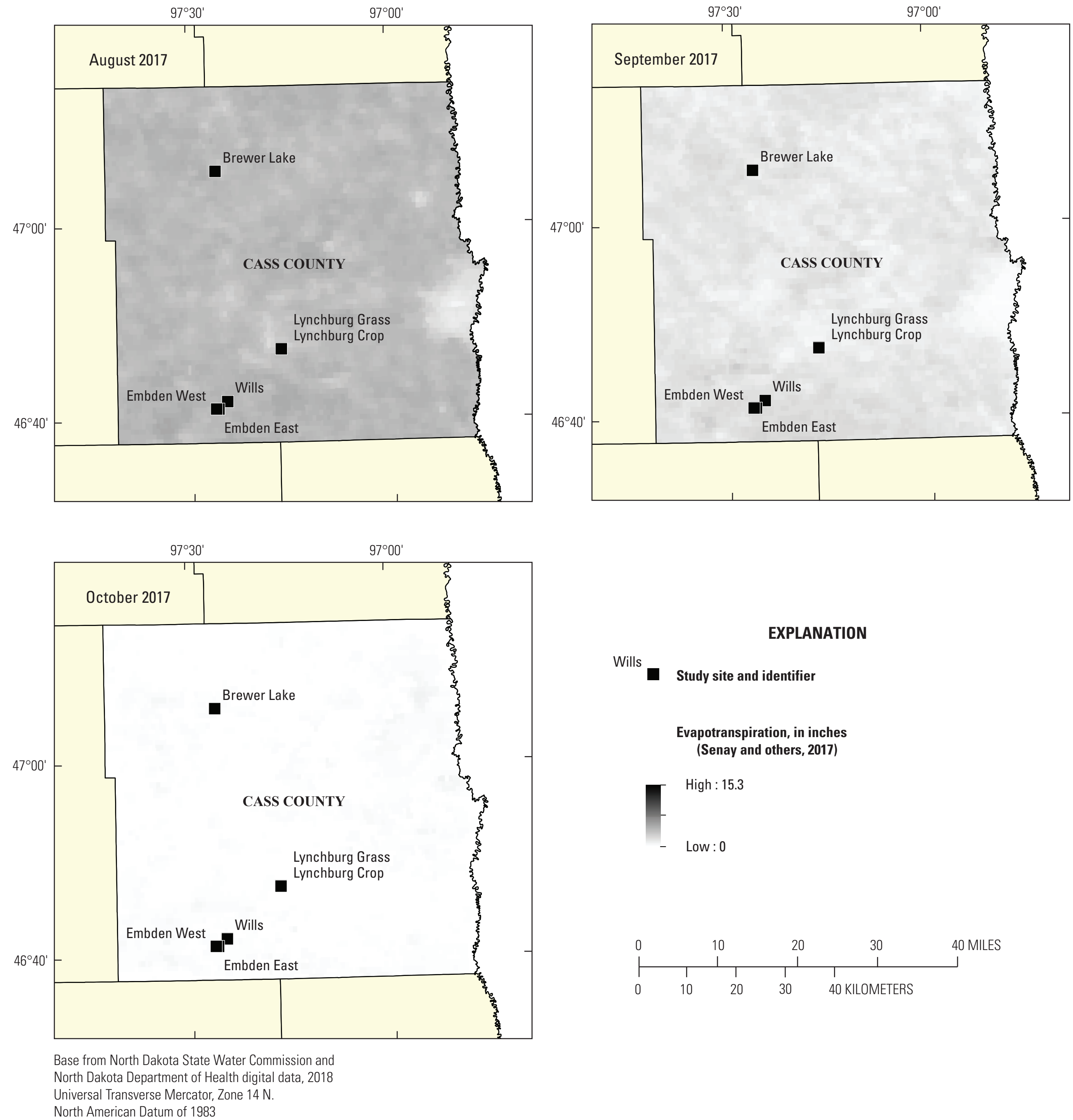


Figure 5. Estimated monthly evapotranspiration for May–October 2017 for Cass County, North Dakota, derived from the Operational Simplified Surface Energy Balance model.—Continued

Measured and Estimated Daily Available Soil-Water Storage

Measured daily AWS values for the two individual depth intervals were determined using the calibrated soil volumetric water-content data for the two individual depth intervals collected at each site, and the two daily AWS values were summed to obtain one AWS value for the total 2 feet of soil depth (Vining, 2020). Measured daily AWS for each individual depth interval was determined as a fraction of the maximum available soil-water storage using equation 7 (Huffman and others, 2013; Klute, 1986):

$$AWS_d = (1 - [V - W] \div [F - W]) \times AWS_{max} \quad (7)$$

where

AWS_d is daily AWS, in inches;
V is the adjusted soil volumetric water content, in percent;
W is permanent wilting point, in percent;
F is field capacity, in percent; and
AWS_{max} is maximum available soil-water storage in 1 foot of soil, in inches, calculated as $(F-W) \times 12 \div 100$ (table 5).

AWS_d reaches the maximum (AWS_{max}) when the soil is dry ($V=W$) and is zero when the soil is wetted to field capacity ($V=F$).

AWS_{max} for the general soil type at each study site was estimated as the difference between published mean values of field capacity volumetric water content and permanent wilting point volumetric water content for that soil type multiplied by 2 feet of soil depth (Ward and Trimble, 2004; Huffman and others, 2013).

Estimated values of daily AWS for the study sites were computed as running totals of estimated changes in daily AWS. Estimated daily AWS values of zero indicate that the top 2 feet of soil depth is at field capacity. Additional water applied to the soil would cause soil saturation and soil percolation to depths greater than 2 feet or to groundwater (hereafter soil percolation) or would potentially produce runoff. Estimated changes in daily AWS were determined using various water-balance techniques (Hornberger and others, 1998; Ward and Trimble, 2004; Vining, 2007), which can be expressed using equation 8:

$$\Delta AWS = ET - P + G + RO \quad (8)$$

where

ΔAWS is estimated change in daily AWS, in inches;
ET is daily ET loss, in inches;
P is daily precipitation gain, in inches;
G is daily soil percolation loss, in inches; and
RO is daily surface runoff loss, in inches.

Of the variables in equation 8, P is the easiest to measure, whereas ET and G are often determined using more complicated measurement or modeling techniques. RO can be measured on-site or can be estimated using data from nearby streamgages if RO losses to storage are negligible. For this study, $G+RO$ was estimated using an equation adapted from Vining (2007). The estimated change in daily AWS (ΔAWS_d) was determined from daily PET plus daily runoff plus soil percolation loss minus daily total precipitation (eq. 9):

$$\Delta AWS_d = (a \times PET_d \times \sin[0.24 \times M] + b \times D_d - c \times P_d) \quad (9)$$

where

ΔAWS_d is estimated change in daily AWS, in inches;
PET_d is daily PET, in inches;
sin is the trigonometric sine function for angles measured in radians;
M is month of the year (January through December) using the values 1 to 12;
D_d is estimated daily runoff plus soil percolation ($G+RO$ in eq. 8) derived from precipitation and antecedent AWS input, in inches;
P_d is daily total precipitation, in inches; and
a, b, and c are coefficients.

D_d was computed as a fraction of the positive differences between daily precipitation and previous-day estimated AWS, and was adapted from the concept of a precipitation-driven surface-runoff technique into wetlands (Vining, 2007; eq. 10):

Table 5. Values of soil permanent wilting point, soil field capacity, and maximum available soil-water storage in 1 foot of soil for the six study sites in Cass County, North Dakota.

[W, soil permanent wilting point; F, soil field capacity; AWS_{max}, maximum available soil-water storage in 1 foot of soil]

Study site (fig. 1)	W, in percent	F, in percent	AWS_{max}, in inches
Brewer Lake	7	15	0.96
Embden East	8	17	1.08
Embden West	13	23	1.20
Lynchburg Crop	26	40	1.68
Lynchburg Grass	26	40	1.68
Wills	12	22	1.20

$$D_d = 0.5 \times (P_d - AWS_{d-1})^{1.5} \text{ If } D_d < 0, \text{ then } D_d = 0 \qquad (10)$$

where

P_d is daily total precipitation, in inches; and

AWS_{d-1} is the estimated AWS from the previous day, in inches.

Coefficients *a*, *b*, and *c* in equation 9 were unique for each study site (table 6) to best relate estimated change in daily AWS to measured change in daily AWS determined from adjusted soil volumetric water-content values. Equation coefficients were determined by examining the correspondence between the estimated and measured daily values visually and by optimizing statistical correlation coefficients from linear regressions between the measured and estimated daily values (Jetten and others, 1999).

Following is an example to calculate *AWS* for May 9, 2016 (month=5) at the Brewer Lake study site using information from table 6 and Vining (2020) in equations 9 and 10. If PET=0.32 inch, P_d=0.05 inch, and AWS_{d-1}=0.343 inch, then $D_d=0.5\times(0.05-0.32)^{1.5}=0$ inch and $\Delta AWS_d=(0.14\times0.32\times\sin[0.24\times5]+0.33\times0-0.47\times0.05)=0.018$ inch. The sine function is calculated for angles in radians. Estimated *AWS* for May 9 is then 0.343+0.018=0.361 inch.

Estimated Daily Runoff Plus Soil Percolation

Although runoff was not measured at the study sites, runoff presumably occurred on some days from snowmelt during February and March of 2017 and from rainfall during other periods. Periods of likely runoff are indicated by the hydrographs of daily mean discharge for May 2016–October 2017 at USGS streamgage 05059700 Maple River near Enderlin, N. Dak. (fig. 6*A*), and streamgage 05060100 Maple River below Mapleton, N. Dak. (fig. 6*B*; U.S. Geological Survey, 2018).

Hydrological conditions at the four sandy soil study sites were considered representative of western Cass County, N. Dak., upstream from the streamgage near Enderlin, and hydrological conditions at the two clay soil study sites were considered representative of central Cass County upstream from the streamgage near Mapleton (Prochnow and others, 1985). For each 6-month period May–October 2016 and 2017, estimated runoff plus soil percolation, in feet, was multiplied by the contributing drainage area for a streamgage, in acres, to calculate the volumes of runoff plus soil percolation, in acre-feet. Total flow volume at a streamgage for each 6-month period, in acre-feet, was calculated using the sum of daily mean discharges, in cubic feet per second, for each 6-month period multiplied by 86,400 seconds per day and divided by 43,560 square feet per acre. Comparison of the flow volume for a period at a streamgage to the estimated runoff plus soil percolation volume for the contributing area of a streamgage will provide a fraction of runoff plus soil percolation that could be considered runoffs. The remaining fraction of the runoff plus soil percolation could be considered soil percolation.

Measured and Estimated Monthly Available Soil-Water Storage

Measured monthly AWS values for each study site were determined as the end-of-month values from the measured daily AWS values for each study site. The measured monthly AWS values at a site incorporate all hydrometeorological events that occurred at a site during any given month and thus serve as the best possible point of reference for evaluating two methods that were used for deriving monthly estimates of AWS.

Estimations of monthly AWS used daily precipitation and PET data that were aggregated to monthly totals and monthly ET data in water-balance techniques to evaluate the effect of PET and ET on AWS calculations. Monthly runoff plus soil percolation values for a study site were not aggregated from daily values because different patterns of daily precipitation during a month that sum to the same monthly total could produce different runoff patterns. If precipitation fell uniformly each day throughout the month, a small but steady amount of runoff or soil percolation could occur; however, if precipitation fell in just a few days during a month, then considerable amounts of runoff could occur quickly (similar to flash-flooding conditions). For these reasons, no values of monthly runoff plus soil percolation were estimated for the study sites.

Table 6. Coefficients used for the estimation of the change in daily available soil-water storage for the six study sites in Cass County, North Dakota.

Study site (fig. 1)	Coefficient (eq. 9)		
	a	***b***	***c***
Brewer Lake	0.14	0.33	0.47
Embden East	0.25	0.50	1.00
Embden West	0.17	0.33	0.67
Lynchburg Crop	0.15	0.20	0.48
Lynchburg Grass	0.27	0.33	0.27
Wills	0.07	0.20	0.30

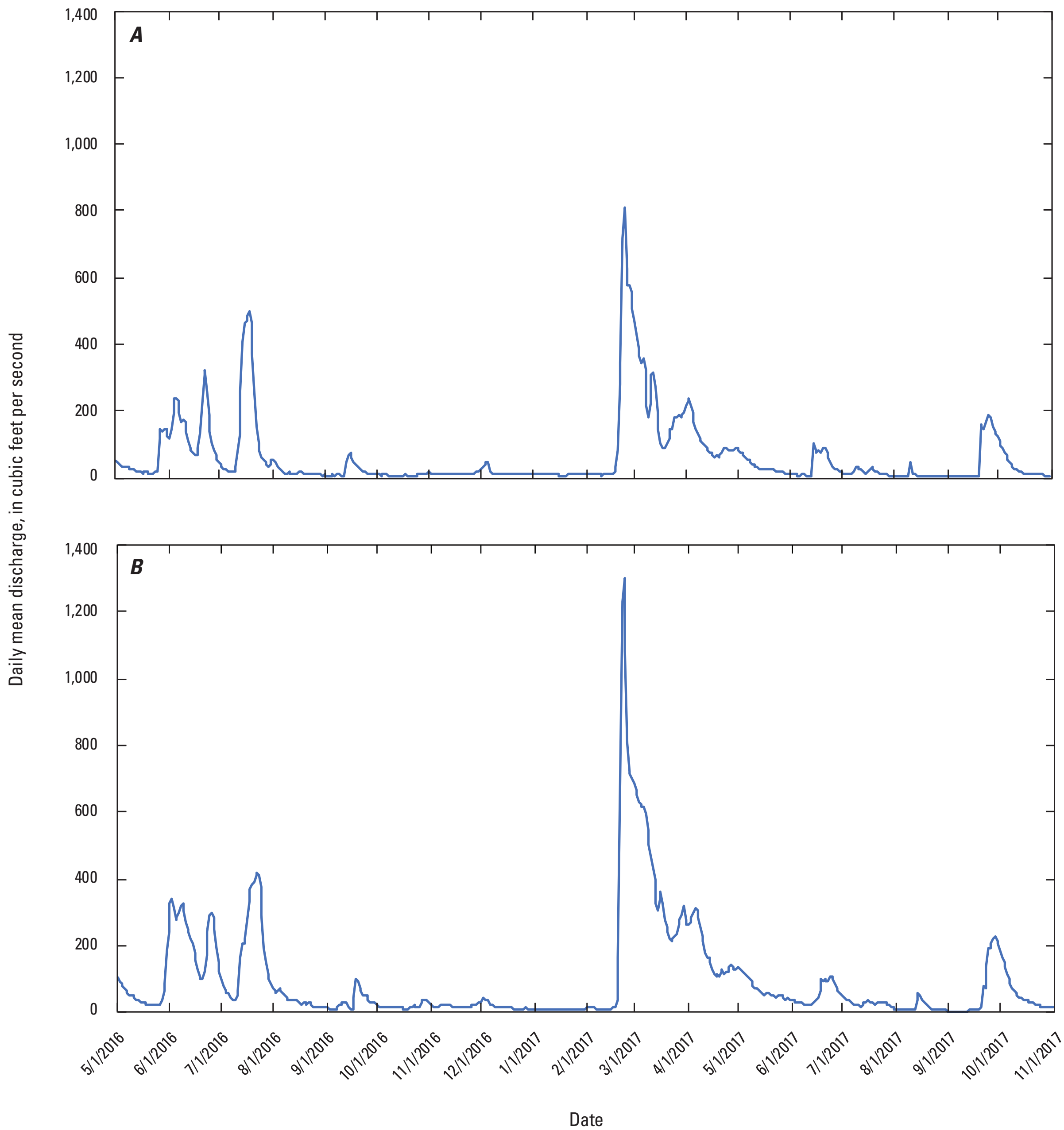


Figure 6. Daily mean discharge on the Maple River, North Dakota, May 2016–October 2017. *A*, U.S. Geological Survey (USGS) streamgage 05059700 Maple River near Enderlin, N. Dak. *B*, USGS streamgage 05060100 Maple River below Mapleton, N. Dak.

Both methods for estimating monthly AWS were based on the water-balance technique used in equation 9 for the daily AWS estimates. Both methods used monthly precipitation data; however, both methods excluded a monthly variable for runoff plus soil percolation. The first method used monthly PET data obtained from NDAWN climate stations, and the second method used ET estimates from SSEBop.

The water-balance equation used to estimate the monthly change in AWS using monthly PET and precipitation was developed (eq. 11):

$$\Delta AWS_m = (a \times PET_m \times \sin[0.24 \times M] - b \times P_m) \quad (11)$$

where

ΔAWS_m is the estimated change in monthly AWS, in inches;

PET_m is monthly PET, in inches;

sin is the trigonometric sine function for angles measured in radians;

M is month of the year (January through December) using the values 1 to 12;

P_m is monthly total precipitation, in inches; and *a* and *b* are coefficients (table 7).

The water-balance equation (eq. 12) used to estimate the monthly change in AWS using monthly ET and precipitation was:

$$\Delta AWS_m = (a \times ET_m - b \times P_m) \quad (12)$$

where

ΔAWS_m is the estimated change in monthly AWS, in inches;

ET_m is monthly ET from the SSEBop model, in inches;

P_m is monthly precipitation, in inches; and

a and *b* are coefficients (table 8).

Monthly PET, ET, and precipitation data for the six study sites (table 9) were used in the two water-balance equations to estimate ΔAWS_m using PET (eq. 11) and ET (eq. 12) for each study site (table 10). The equation coefficients (tables 7 and 8, respectively) were determined by visual calibration and by optimizing statistical correlation coefficients between estimated and measured values of the change in monthly AWS (Jetten and others, 1999). Water-balance equations were unique for each study site to best relate estimated monthly values of ΔAWS and AWS calculated using PET and ET to monthly values of AWS and ΔAWS determined from measured values (table 10).

Regression analyses were performed to investigate whether using values of PET or ET might provide a more accurate estimate of monthly AWS for a grouping of all the sandy soil study sites and for a grouping of both clay soil study sites. For each grouping of study sites, two regression analyses were performed, one between measured monthly AWS and estimated monthly AWS determined using PET and the other between measured monthly AWS and estimated monthly AWS determined using ET.

Table 7. Coefficients used for the estimation of the change in monthly available soil-water storage for the six study sites in Cass County, North Dakota, using potential evapotranspiration.

Study site (fig. 1)	Coefficient (eq. 11)	
	a	*b*
Brewer Lake	0.25	1.00
Embden East	0.22	0.90
Embden West	0.22	0.93
Lynchburg Crop	0.17	0.54
Lynchburg Grass	0.20	0.60
Wills	0.20	0.90

Table 8. Coefficients used for the estimation of the change in monthly available soil-water storage for the six study sites in Cass County, North Dakota, using evapotranspiration.

Study site (fig. 1)	Coefficient (eq. 12)	
	a	*b*
Brewer Lake	0.3	0.4
Embden East	0.4	0.7
Embden West	0.3	0.6
Lynchburg Crop	0.4	0.6
Lynchburg Grass	0.5	0.5
Wills	0.3	0.6

Table 9. Monthly precipitation, potential evapotranspiration, and evapotranspiration for May–October in 2016 and 2017 for the six study sites in Cass County, North Dakota.

[PET, potential evapotranspiration; ET, evapotranspiration]

Month	Precipitation, in inches	PET, in inches	ET, in inches
Brewer Lake			
May 2016	4.50	8.42	1.02
June 2016	1.79	7.85	2.44
July 2016	3.78	6.37	5.79
August 2016	2.43	6.29	4.69
September 2016	2.95	4.38	3.58
October 2016	1.53	2.68	0.47
May 2017	0.63	7.66	0.43
June 2017	2.03	8.67	2.56
July 2017	1.65	7.75	4.02
August 2017	0.87	5.87	3.66
September 2017	5.05	4.49	1.26
October 2017	0.04	3.80	0.00
Embden East			
May 2016	1.86	8.94	0.00
June 2016	1.84	8.95	2.87
July 2016	3.49	7.31	6.06
August 2016	2.19	6.24	3.70
September 2016	2.85	4.74	3.03
October 2016	1.97	3.03	0.00
May 2017	0.87	8.20	0.31
June 2017	1.53	9.32	2.20
July 2017	1.44	8.11	4.49
August 2017	1.96	5.57	4.29
September 2017	2.72	4.72	2.09
October 2017	0.47	3.64	0.12
Embden West			
May 2016	1.86	8.94	0.00
June 2016	1.84	8.95	2.87
July 2016	3.49	7.31	6.06
August 2016	2.19	6.24	3.70
September 2016	2.85	4.74	3.03
October 2016	1.97	3.03	0.00
May 2017	0.87	8.20	0.31
June 2017	1.53	9.32	2.20
July 2017	1.44	8.11	4.49
August 2017	1.96	5.57	4.29
September 2017	2.72	4.72	2.09
October 2017	0.47	3.64	0.12

Table 9. Monthly precipitation, potential evapotranspiration, and evapotranspiration for May–October in 2016 and 2017 for the six study sites in Cass County, North Dakota.—Continued

[PET, potential evapotranspiration; ET, evapotranspiration]

Month	Precipitation, in inches	PET, in inches	ET, in inches
Lynchburg Crop			
May 2016	1.86	8.94	0.00
June 2016	1.84	8.95	0.55
July 2016	3.49	7.31	6.69
August 2016	2.19	6.24	5.12
September 2016	2.85	4.74	3.31
October 2016	1.97	3.03	0.00
May 2017	0.87	8.20	0.20
June 2017	1.53	9.32	1.22
July 2017	1.44	8.11	3.82
August 2017	1.96	5.57	3.62
September 2017	2.72	4.72	1.14
October 2017	0.47	3.64	0.00
Lynchburg Grass			
May 2016	1.86	8.94	0.00
June 2016	1.84	8.95	0.55
July 2016	3.49	7.31	6.69
August 2016	2.19	6.24	5.12
September 2016	2.85	4.74	3.31
October 2016	1.97	3.03	0.00
May 2017	0.87	8.20	0.20
June 2017	1.53	9.32	1.22
July 2017	1.44	8.11	3.82
August 2017	1.96	5.57	3.62
September 2017	2.72	4.72	1.14
October 2017	0.47	3.64	0.00
Wills			
May 2016	1.86	8.94	0.00
June 2016	1.84	8.95	1.14
July 2016	3.49	7.31	6.18
August 2016	2.19	6.24	4.69
September 2016	2.85	4.74	3.23
October 2016	1.97	3.03	0.00
May 2017	0.87	8.20	0.16
June 2017	1.53	9.32	1.34
July 2017	1.44	8.11	4.41
August 2017	1.96	5.57	4.57
September 2017	2.72	4.72	2.28
October 2017	0.47	3.64	0.00

Results of Water-Balance Techniques and Available Soil-Water Storage Analyses

Data obtained from field monitoring at the six study sites were used in water-balance analyses to determine AWS on daily and monthly time steps. Soil volumetric water-content data, precipitation data, and PET data were available in daily time steps, and these daily data were aggregated into monthly time steps. ET data from the SSEBop model were available only monthly, so comparisons on the use of ET and PET data in water-balance equations for estimating AWS were performed on monthly time steps.

Water-Balance Conditions

Estimated daily AWS values (Vining, 2020) were influenced mostly by daily precipitation and PET data and by estimated daily runoff plus soil percolation that were used in water-balance equations. Monthly precipitation values (table 9) were an important factor in the monthly water-budget computations for estimating monthly AWS. October 2017 was the driest month for all six of the study sites; monthly precipitation was from 0.04 inch at the Brewer lake site and 0.47 inch at the other five sites. The previous month, September 2017, was the wettest month at the Brewer lake site and the third wettest month for the other five sites.

Monthly PET values were larger than the corresponding monthly ET values at all study sites because PET is an upper limit for evapotranspiration for a well-watered field of short grass (table 9). Monthly ET values estimated from the SSEBop model result from the incorporation of all monthly water-balance processes at a location. Thus, AWS values calculated using ET values may be more representative of monthly soil-water conditions than AWS calculated using PET values.

Estimated ET values for 2016–17 at each study site (table 9) indicate some differences perhaps caused by precipitation and crop growth. At the Embden and Lynchburg sites, the different crops grown in 2016 (wheat at Embden and sugar beets at Lynchburg; table 1) and 2017 (corn at Embden and soybeans at Lynchburg; table 1) may have affected ET. In addition, corn is usually a greater user of water than wheat during the growing season, and beets often use greater amounts of water than soybeans (Bauder and Ennen, 1981; North Dakota State University, 2017). At the grassland sites, the greater amount of precipitation at the Brewer Lake site in May 2016 may have stimulated faster grass growth and greater ET (1.02 inches) than at the Lynchburg Grass site (0 inches) and the Wills site (0 inches).

No water was detected in any of the piezometer bore holes during installation, and no water was detected in the piezometers at the Brewer Lake and Wills sites during any of the site visits. Water depth was measured from the bottoms of the piezometer tubes on nine occasions at the Embden East site (fig. 7*A*) and on seven occasions at the Lynchburg Crop site (fig. 7*B*). In all cases the measured water depths were below the depths of the deepest soil volumetric water-content probes.

Daily Available Soil-Water Storage and Runoff Plus Soil Percolation Analyses

Values of daily AWS and runoff plus soil percolation are presented for the four sandy soil sites (Brewer Lake, Embden East, Embden West, and Wills) and for the two clay soil sites (Lynchburg Crop and Lynchburg Grass) (Vining, 2020). Results of regression analyses are presented to provide comparison between the sandy soil sites and clay soil sites. Comparisons of AWS are also made for the various crops that were grown between cropland and nearby grasslands.

Daily Available Soil-Water Storage for Sandy Soil Sites

Measured daily AWS was less than 2 inches at all four sandy soil sites during May–October 2016 and 2017 indicating that the soils could hold less than 2 inches of water in 2 feet of soil on a daily basis (Vining, 2020). For the Brewer Lake site, comparisons of measured and estimated daily values of AWS indicated fair agreement during May–October 2016 and during May–October 2017 (fig. 8). The correlation coefficient between the estimated and measured AWS values was 0.69, indicating a fair agreement between the estimated and measured values (table 11). Daily precipitation amounts greater than 1 inch during May and July 2016 likely increased soil volumetric water content, reduced AWS, and perhaps generated runoff.

For the Embden East site, comparisons of measured and estimated daily values of AWS indicated poor agreement (fig. 9). Precipitation data for 2016 and 2017 were obtained from the Leonard, N. Dak., NDAWN station, about 9.5 miles east-northeast of the Embden East site (fig. 1). The correlation coefficient between measured and estimated daily AWS was 0.12 (table 11).

For the Embden West site, comparisons of measured and estimated daily values of AWS indicated fair agreement between values (fig. 10). Precipitation data used for this site, obtained from the Leonard, N. Dak., NDAWN station, were the same data used for the Embden East site. The correlation coefficient between estimated and measured AWS for May–October 2016 and May–October 2017 was 0.54 (table 11). The Embden West site was near tile drainage but effects from tile drainage were not apparent.

At the Wills study site, values of AWS were often less than 0.5 inch (fig. 11), considerably less than at the other sandy soil sites. Measured values were mostly zero inches in 2016, and estimated values were less than 0.25 inch, and in 2017 measured values were frequently greater than estimated values. Observations during soil sampling at the site

Table 10. Estimated monthly values of estimated change in available soil-water storage (ΔAWS) and available soil-water storage (AWS) using potential evapotranspiration and evapotranspiration, and monthly values of AWS and ΔAWS from measured values for May–October in 2016 and 2017 for the six study sites in Cass County, North Dakota.

[ΔAWS, estimated change in monthly available soil-water storage; AWS, available soil-water storage; PET, potential evapotranspiration; ET, evapotranspiration]

Month	Values, in inches					
	Estimated ΔAWS using PET[1]	Estimated AWS using PET	Estimated ΔAWS using ET[2]	Estimated AWS using ET	Measured AWS	ΔAWS from measured
Brewer Lake						
May 2016	−2.54	0.00	−1.49	0.00	0.00	0.00
June 2016	0.15	0.15	0.02	0.02	0.71	0.71
July 2016	−2.20	0.00	0.22	0.24	0.48	−0.23
August 2016	−0.95	0.00	0.43	0.67	0.73	0.25
September 2016	−2.04	0.00	−0.11	0.57	0.31	−0.42
October 2016	−1.08	0.00	−0.47	0.10	0.05	−0.26
May 2017	1.15	1.15	−0.12	0.00	0.84	0.00
June 2017	0.12	1.27	−0.04	0.00	0.91	0.07
July 2017	0.27	1.55	0.54	0.54	1.37	0.46
August 2017	0.51	2.06	0.75	1.30	0.85	−0.52
September 2017	−4.12	0.00	−1.64	0.00	0.03	−0.82
October 2017	0.60	0.60	−0.02	0.00	0.58	0.55
Embden East						
May 2016	0.16	0.16	−1.30	0.00	0.00	0.00
June 2016	0.30	0.46	−0.14	0.00	0.96	0.96
July 2016	−1.54	0.00	−0.02	0.00	1.55	0.59
August 2016	−0.68	0.00	−0.05	0.00	1.91	0.36
September 2016	−1.70	0.00	−0.78	0.00	0.66	−1.25
October 2016	−1.32	0.00	−1.38	0.00	0.09	−0.57
May 2017	0.90	0.90	−0.48	0.00	0.36	0.36
June 2017	0.66	1.55	−0.19	0.00	0.19	−0.17
July 2017	0.48	2.03	0.79	0.79	1.26	1.07
August 2017	−0.61	1.42	0.34	1.13	1.00	−0.26
September 2017	−1.58	0.00	−1.05	0.08	0.01	−0.99
October 2017	0.12	0.12	−0.28	0.00	0.18	0.17
Embden West						
May 2016	0.10	0.10	−1.12	0.00	0.00	0.00
June 2016	0.24	0.35	−0.24	0.00	0.00	0.00
July 2016	−1.65	0.00	−0.28	0.00	0.09	0.09
August 2016	−0.75	0.00	−0.20	0.00	0.72	0.63
September 2016	−1.78	0.00	−0.80	0.00	0.00	−0.72
October 2016	−1.38	0.00	−1.18	0.00	0.00	0.00
May 2017	0.87	0.87	−0.43	0.00	0.16	0.16
June 2017	0.61	1.48	−0.26	0.00	0.04	−0.12
July 2017	0.43	1.92	0.48	0.48	1.17	1.13
August 2017	−0.67	1.25	0.11	0.59	0.63	−0.54
September 2017	−1.67	0.00	−1.01	0.00	0.24	−0.39
October 2017	0.10	0.10	−0.25	0.00	0.43	0.19

Table 10. Estimated monthly values of estimated change in available soil-water storage (ΔAWS) and available soil-water storage (AWS) using potential evapotranspiration and evapotranspiration, and monthly values of AWS and ΔAWS from measured values for May–October in 2016 and 2017 for the six study sites in Cass County, North Dakota.—Continued

[ΔAWS, estimated change in monthly available soil-water storage; AWS, available soil-water storage; PET, potential evapotranspiration; ET, evapotranspiration]

Month	Values, in inches					
	Estimated ΔAWS using PET[1]	Estimated AWS using PET	Estimated ΔAWS using ET[2]	Estimated AWS using ET	Measured AWS	ΔAWS from measured
Lynchburg Crop						
May 2016	0.41	0.41	−1.12	0.00	0.00	0.00
June 2016	0.52	0.93	−0.88	0.00	0.00	0.00
July 2016	−0.65	0.28	0.58	0.58	0.00	0.00
August 2016	−0.19	0.09	0.73	1.32	0.57	0.57
September 2016	−0.87	0.00	−0.39	0.93	0.53	−0.04
October 2016	−0.72	0.00	−1.18	0.00	0.34	−0.19
May 2017	0.83	0.83	−0.44	0.00	1.49	1.49
June 2017	0.74	1.57	−0.43	0.00	1.06	−0.43
July 2017	0.59	2.17	0.66	0.66	0.45	−0.61
August 2017	−0.17	2.00	0.27	0.94	1.43	0.98
September 2017	−0.80	1.20	−1.18	0.00	0.48	−0.95
October 2017	0.16	1.36	−0.28	0.00	1.31	0.83
Lynchburg Grass						
May 2016	0.55	0.55	−0.93	0.00	0.00	0.00
June 2016	0.67	1.22	−0.64	0.00	0.21	0.21
July 2016	−0.64	0.58	1.60	1.60	0.00	−0.21
August 2016	−0.14	0.44	1.46	3.07	1.28	1.28
September 2016	−0.92	0.00	0.23	3.29	0.12	−1.16
October 2016	−0.77	0.00	−0.99	2.31	0.00	−0.12
May 2017	1.01	1.01	−0.34	1.97	0.14	0.14
June 2017	0.93	1.94	−0.15	1.82	2.04	1.90
July 2017	0.75	2.68	1.19	3.01	2.38	0.34
August 2017	−0.13	2.56	0.83	3.84	3.04	0.66
September 2017	−0.85	1.71	−0.79	3.05	0.83	−2.21
October 2017	0.21	1.92	−0.24	2.81	1.96	1.13
Wills						
May 2016	−0.01	0.00	−1.12	0.00	0.00	0.00
June 2016	0.12	0.12	−0.76	0.00	0.00	0.00
July 2016	−1.69	0.00	−0.24	0.00	0.02	0.02
August 2016	−0.80	0.00	0.09	0.09	0.00	−0.02
September 2016	−1.78	0.00	−0.74	0.00	0.00	0.00
October 2016	−1.36	0.00	−1.18	0.00	0.00	0.00
May 2017	0.75	0.75	−0.47	0.00	0.42	0.42
June 2017	0.47	1.22	−0.52	0.00	0.48	0.06
July 2017	0.32	1.53	0.46	0.46	0.33	−0.15
August 2017	−0.72	0.82	0.19	0.65	0.33	0.00
September 2017	−1.66	0.00	−0.95	0.00	0.20	−0.13
October 2017	0.07	0.07	−0.28	0.00	0.54	0.34

[1]Using equation 11.

[2]Using equation 12.

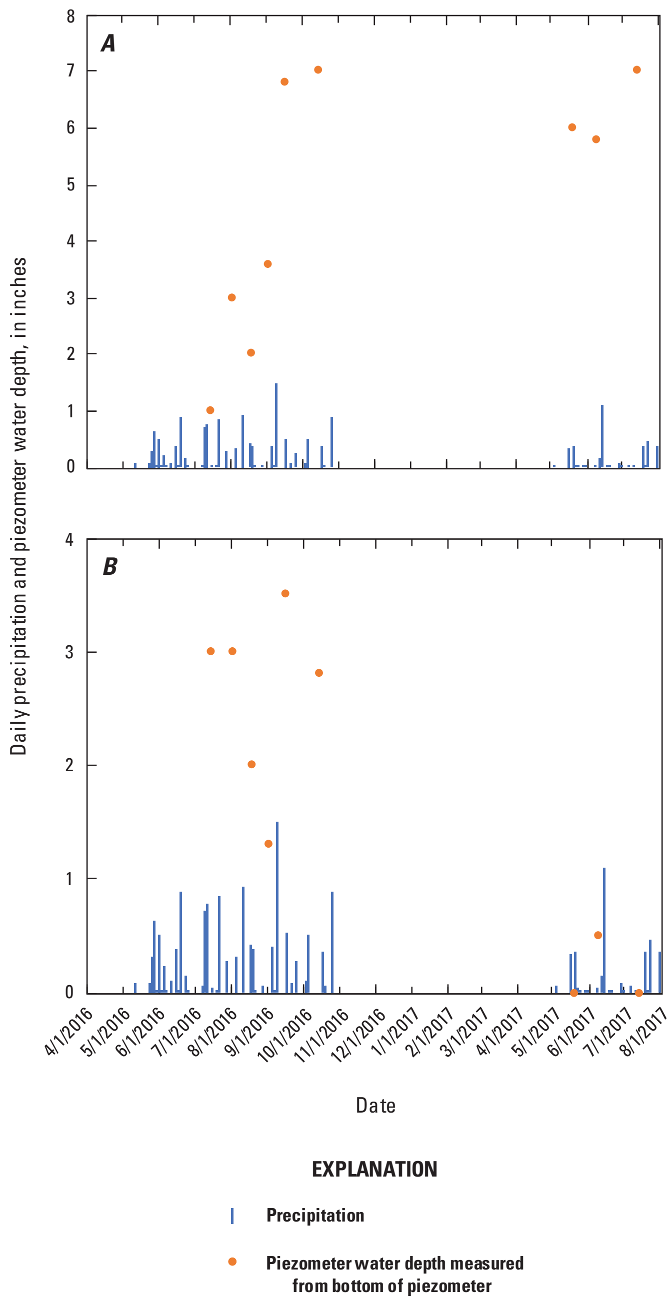


Figure 7. Water depths measured from the bottoms of piezometer tubes and daily precipitation (North Dakota State University, 2017) at two study sites in Cass County, North Dakota. *A*, Embden East study site. *B*, Lynchburg Crop study site.

indicated that the soil was often wet, even near the surface. During 2017, precipitation amounts occasionally greater than 0.75 inch seemed to be directly related to the sharp decreases in measured AWS values and could have generated runoff. Grass residue and rainfall in 2016 and an accumulation of corn plant residue that blew on the site from a nearby field in October 2016 may have restricted evaporation from the soil and kept soil water contents elevated. Activity by burrowing animals at the Wills site destroyed two soil volumetric water-content probes, one at each depth, in late 2016, which resulted in the relocation of the monitoring station about 50 feet to the south in May 2017 into an area with the same soil type and plant growth. The relation between estimated and measured AWS for May 2016 through October 2017 was good with a correlation coefficient of 0.78 (table 11).

Daily Available Soil-Water Storage for Clay Soil Sites

Measured daily AWS for the two clay soil sites indicated that a maximum of about 1.6 and 3.4 inches of water could be stored in 2 feet of soil at the Lynchburg Crop and Lynchburg Grass sites, respectively (figs. 12 and 13, respectively; Vining, 2020). For the Lynchburg Crop site, comparisons of measured and estimated daily values of AWS indicated varying degrees of agreement (fig. 12). Past studies had indicated that clay in soil can affect the function of the soil volumetric water-content probes (Gong and others, 2003). As the clay soil site dried, especially during 2017, visible cracks formed that may have affected the function of the soil volumetric water-content probes and resulted in greater values of measured AWS. Soil cracks also may create paths for the preferential flow of water into the soil (Römkens and Prasad, 2006). During rainfall on September 1, 2017, measured AWS values decreased sharply because of possible preferential water flow into cracks, but then a few days later, soil percolation and drying in the soil cracks may have occurred and AWS values increased sharply (Ritchie and Adams, 1974). The relation of estimated and measured AWS for May 2016 through October 2017 at the Lynchburg Crop site was fair with a correlation coefficient of 0.68 (table 11).

For the Lynchburg Grass site, comparisons of measured and estimated daily values of AWS indicated results similar to those at the Lynchburg Crop site during 2016 but not during 2017 (fig. 13). Lesser amounts of precipitation during 2017 than 2016 resulted in soil drying at both sites and the formation of distinct soil cracks at the Lynchburg Grass site, which may have affected AWS values. Measured daily AWS exceeded 3 inches during parts of August and September 2017 (Vining, 2020). The correlation coefficient between estimated and measured AWS for May 2016 through October 2017 at the Lynchburg Grass site was 0.96 (table 11), which indicates a good relation even with the possible effects of soil cracks.

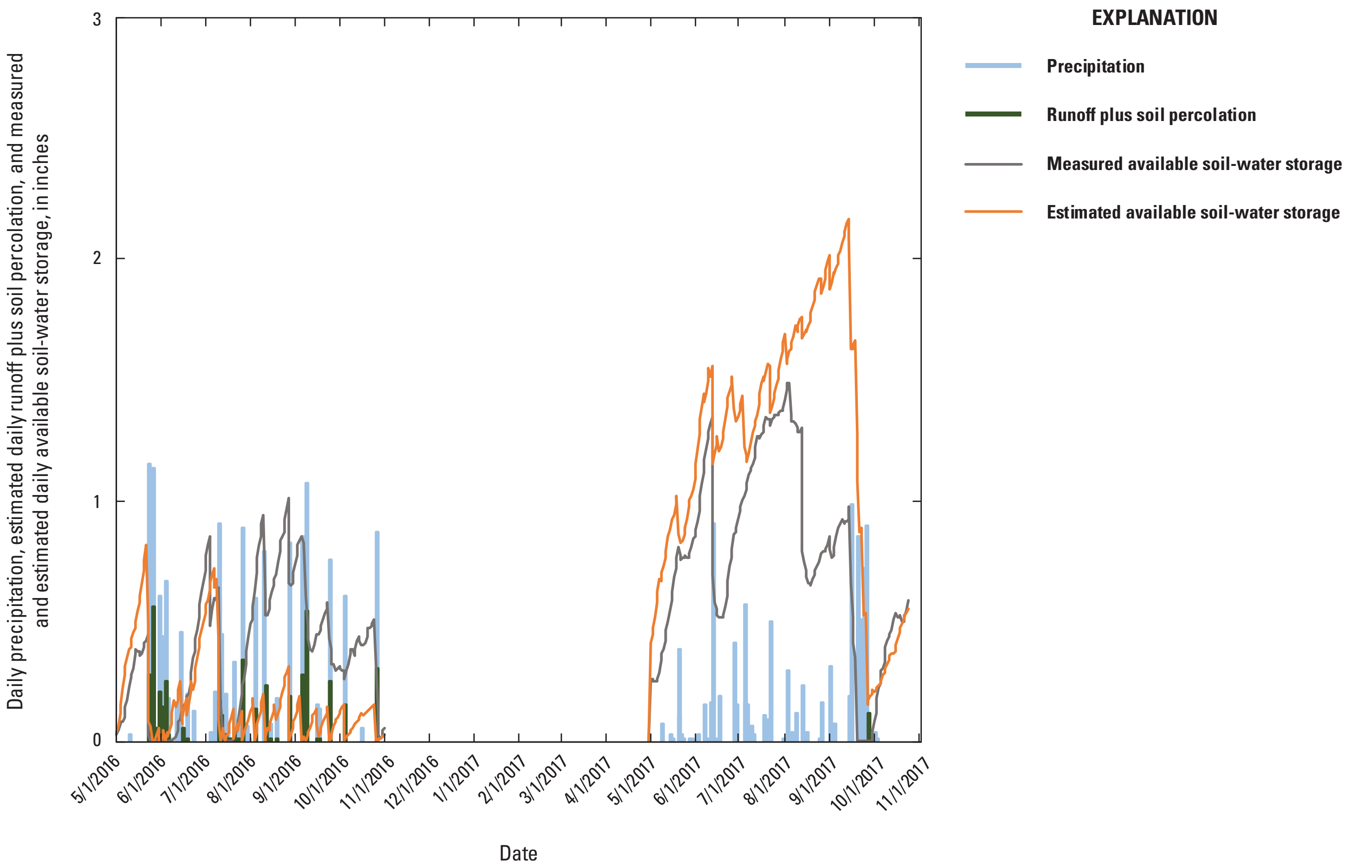


Figure 8. Daily precipitation, estimated runoff plus soil percolation, and measured and estimated daily available soil-water storage for May–October in 2016 and 2017 at the Brewer Lake study site in Cass County, North Dakota.

Table 11. Slopes, intercepts, and correlation coefficients from regressions of estimated and measured daily available soil-water storage for May–October in 2016 and 2017 for the four sandy soil and two clay soil study sites in Cass County, North Dakota.

Study site (fig. 1)	Slope	Intercept	Correlation coefficient
Sandy soil sites			
Brewer Lake	1.17	0.02	0.69
Embden East	0.16	0.65	0.12
Embden West	0.71	0.20	0.54
Wills	0.77	0.03	0.78
Clay soil sites			
Lynchburg Crop	1.16	0.21	0.68
Lynchburg Grass	0.75	0.05	0.96

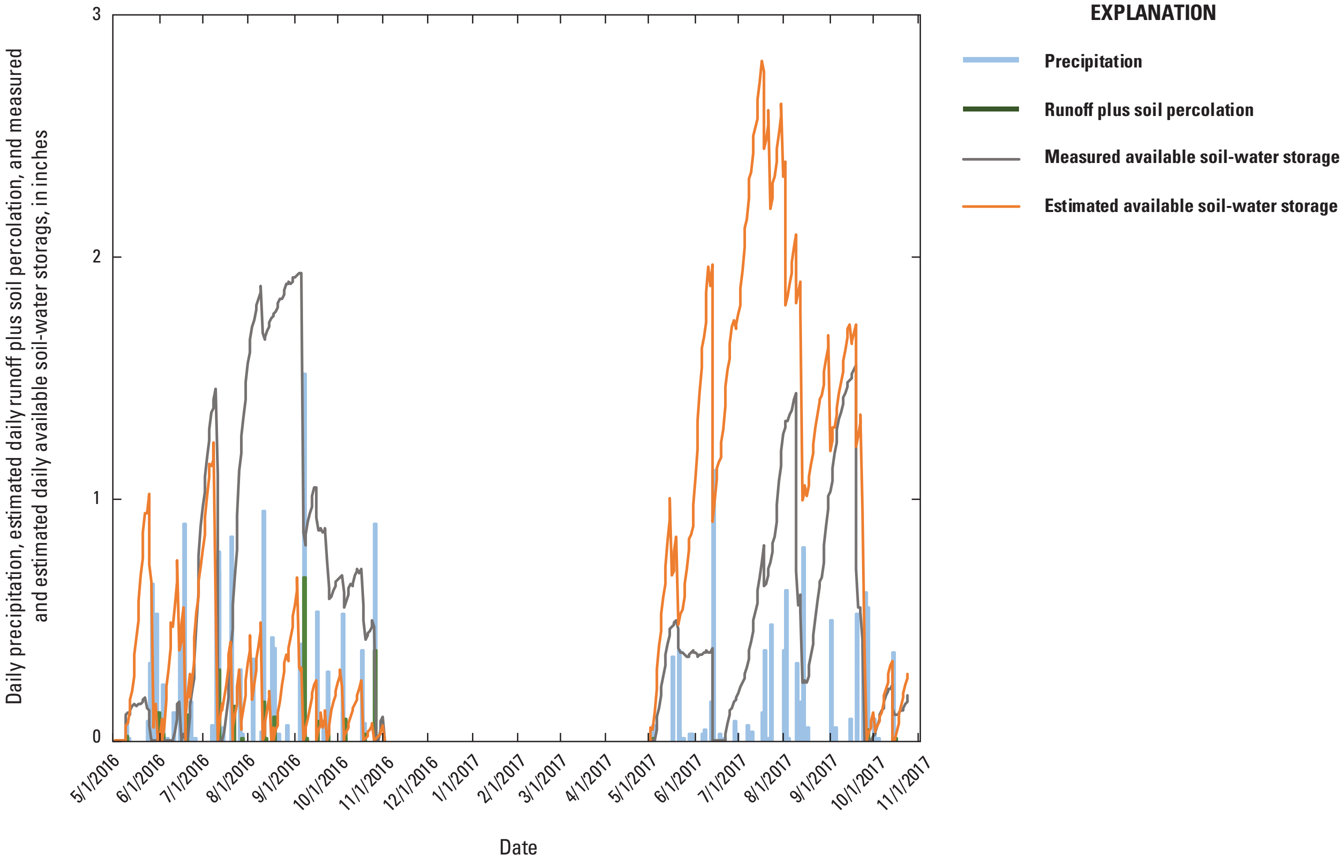


Figure 9. Daily precipitation, estimated runoff plus soil percolation, and measured and estimated daily available soil-water storage for May–October in 2016 and 2017 at the Embden East study site in Cass County, North Dakota.

Daily Runoff Plus Soil Percolation

Estimated daily values of runoff plus soil percolation are shown for the four sandy soil sites (Brewer Lake, Embden East, Embden West, and Wills sites) during May–October 2016 (fig. 14*A*) and 2017 (fig. 14*B*) and for the two clay soil sites (Lynchburg Crop and Lynchburg Grass) during May–October 2016 (fig. 14*C*) and 2017 (fig. 14*D*). All values for 2017 at the Lynchburg Crop site were zero.

Comparisons of daily runoff plus soil percolation for the sandy soil sites (figs. 14*A* and 14*B*) to the discharge hydrograph from the streamgage Maple River near Enderlin (fig. 6*A*) indicate that there is a relation between the occurrences of estimated runoff plus soil percolation and discharge. Flow volumes at the streamgage Maple River near Enderlin during May–October 2016 and 2017 were about 23,820 and 10,840 acre-feet, respectively (U.S. Geological Survey, 2018). The mean estimated runoff plus soil percolation from the four sandy soil study sites (Brewer Lake, Embden East, Embden West, and Wills) for May–October 2016 and 2017 were about 3.95 and 0.31 inches (about 0.329 and 0.026 foot), respectively (table 12). If these estimated values of runoff plus soil percolation were applied across the entire contributing drainage area for the streamgage Maple River near Enderlin (about 509,400 acres), then about 167,600 and 13,240 acre-feet of runoff plus soil percolation would have been generated during May–October 2016 and 2017, respectively. Overall for May–October 2016 and 2017, these results indicated that a maximum of about 19 percent of the estimated daily runoff plus soil percolation from the four sandy soil study sites could be considered runoff to the river ([23,820+10,840 acre-feet]÷[167,600+13,240 acre-feet]) and that the remaining 81 percent could be considered soil percolation.

The Lynchburg Crop and Lynchburg Grass clay soil study sites had mean estimated runoff plus soil percolation that was 0.24 inch less than the sandy soil study sites during May–October 2016 (3.71 inches or about 0.309 foot) and was 0.19 inch less than the sandy soil study sites during May–October 2017 (0.12 inch or about 0.01 foot; table 12). There seems to be a relation between the occurrences of estimated runoff plus soil percolation at the clay soil sites (figs. 14*C* and 14*D*) and discharge at the streamgage Maple River below Mapleton (fig. 6*B*). If these clay soil study sites were representative of the drainage area from the streamgage Maple River near Enderlin to the streamgage Maple River below Mapleton, the additional contributing drainage area would be about 393,000 acres, and the additional flow volumes for May–October 2016 and 2017 would be about 9,730 and

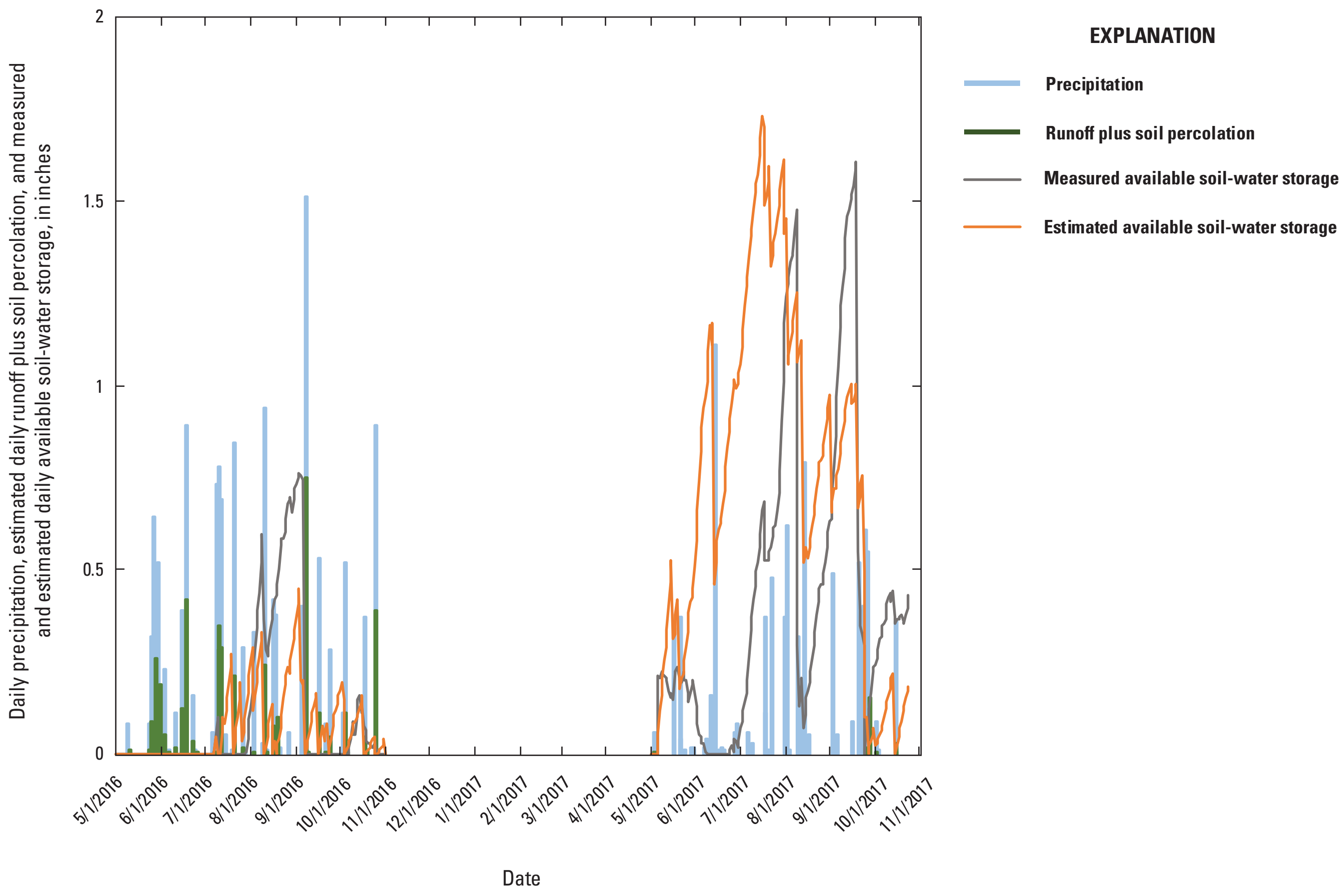


Figure 10. Daily precipitation, estimated runoff plus soil percolation, and measured and estimated daily available soil-water storage for May–October in 2016 and 2017 at the Embden West study site in Cass County, North Dakota.

6,160 acre-feet, respectively (U.S. Geological Survey, 2018). If these mean estimated runoff plus soil percolation values for the two clay soil sites (0.309 and 0.01 foot) was applied across the additional contributing drainage between the two Maple River streamgages (393,000 acres), then about 121,400 and 3,930 acre-feet of runoff plus soil percolation would have been generated during May–October 2016 and 2017, respectively. When compared to the additional flow volume at the Mapleton streamgage, then about 13 percent of the runoff plus soil percolation ([9,730+6,160 acre-feet]÷[121,400+3,930 acre-feet]) could be considered runoff and about 87 percent could be considered soil percolation. The topographic relief near the clay soil sites in central Cass County is very low, which can limit runoff.

Comparisons of Daily Available Soil-Water Storage for Croplands and Grasslands

The different crops grown in 2016 and 2017 at the Embden East and Embden West sites (wheat in 2016, corn in 2017) and at the Lynchburg Crop site (sugar beets in 2016, soybeans in 2017) might have affected AWS (table 13), but the lesser amounts of precipitation in 2017 than in 2016 also likely affected AWS. In North Dakota, corn is usually a greater user of water than wheat during the growing season (Bauder and Ennen, 1981; North Dakota State University, 2017). Greater AWS from possible increased water use was indicated for the corn crop in 2017 than the wheat crop in 2016 at the Embden East and Embden West sites (figs. 9 and 10, respectively). At the Lynchburg Crop site, greater AWS was indicated during the growth of soybeans in 2017 than sugar beets in 2016 (fig. 12), but May–October precipitation in 2017 (8.99 inches) was less than in 2016 (14.27 inches). Actively growing beets often use greater amounts of water than soybeans during a growing season in North Dakota (Bauder and Ennen, 1981; North Dakota State University, 2017), but less precipitation in 2017 than in 2016 likely had a larger effect than crop type on greater AWS in 2017 than in 2016 at the Lynchburg Crop site.

The May–October mean AWS values at the Embden East and Embden West cropland sites were greater than at the nearby Wills grassland site (table 13). Soil dry bulk densities, which were determined during soil sampling, were similar among the three sites (table 3). Similar soil dry bulk densities indicated that similar amounts of soil pore volume existed at the sites, but perhaps because of different plant growth and soil structure, daily AWS at the Wills site (fig. 11) was

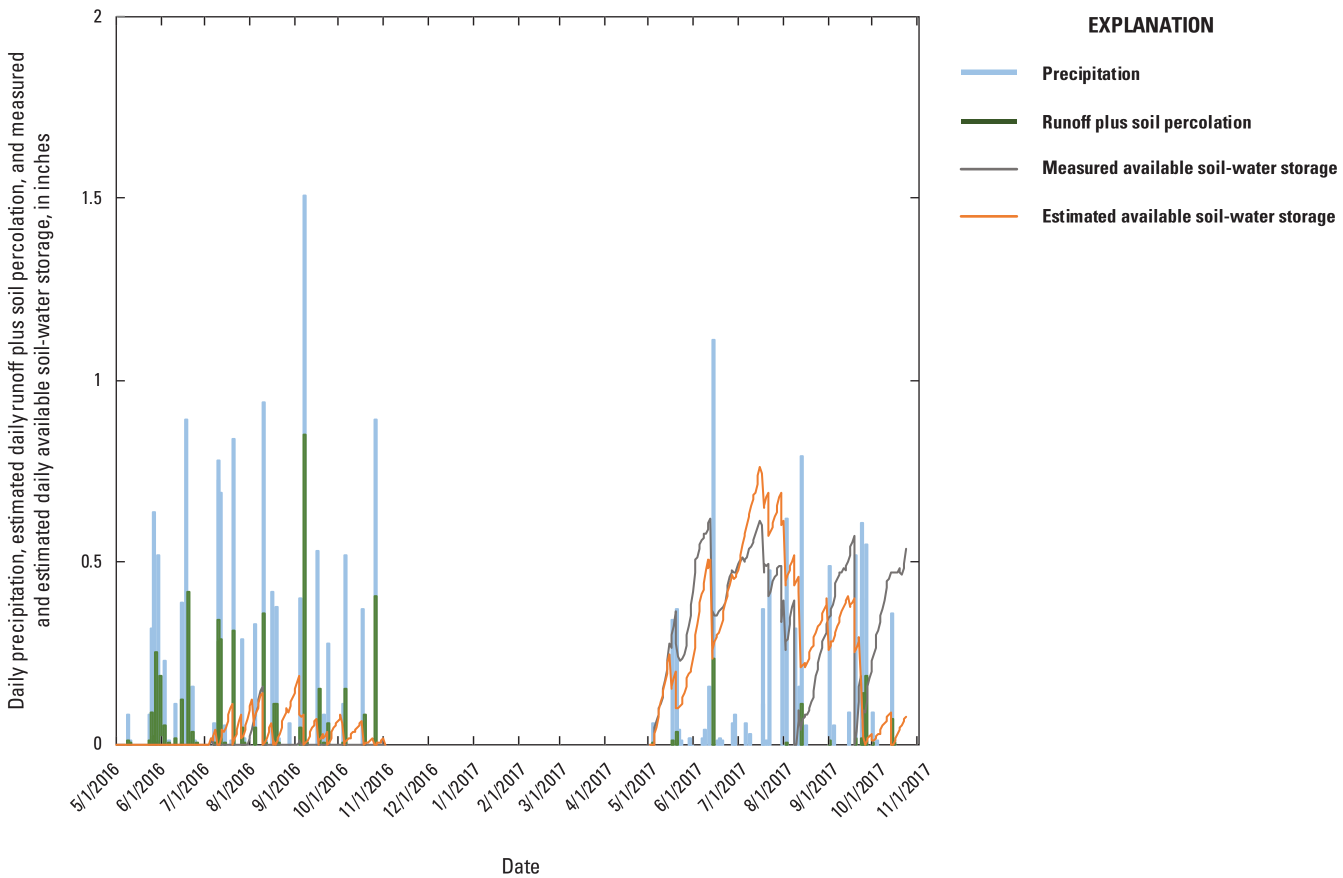


Figure 11. Daily precipitation, estimated runoff plus soil percolation, and measured and estimated daily available soil-water storage for May–October in 2016 and 2017 at the Wills study site in Cass County, North Dakota.

considerably less than at the Embden East (fig. 9) and Embden West (fig. 10) sites during 2016–17. The Wills site has had no cultivation for many years, whereas the cropped Embden East and Embden West sites have had annual cultivation that could have created soil conditions favorable for greater AWS.

In October 2016, surface conditions at the Wills grassland site were complicated by burrowing animals that damaged two soil volumetric water-content probes and by a layer of corn plant residue about 1-foot thick that blew onto the site from an adjacent field. Within 2 months, most of the residue was removed from the study site. The corn plant residue, the effects of burrowing animals on the function of soil volumetric water-content probes, and the need to relocate the station may have had some effect on the water balance and determinations of AWS at the Wills grassland site.

The Lynchburg Crop and Lynchburg Grass sites were a close cropland/grassland pair but estimated and measured daily AWS varied considerably (figs. 12 and 13, respectively). Values of PET, ET, and precipitation were identical for each site because of their proximity (only about 150 feet apart), but the differences in measured soil volumetric water contents at the sites resulted in different equations to estimate daily AWS (table 6). During summer, distinct cracks formed at the Lynchburg Grass site, which has never been tilled, but only small cracks formed in the Lynchburg Crop site where tillage occurs several times each year. During rainfall on September 1, 2017, the presence of soil cracks at the Lynchburg Crop and Grass sites may have had an effect on preferential water flow and allowed measured AWS values to decrease sharply (figs. 12 and 13, respectively). Shortly after the rainfall, measured AWS values increased rapidly because soil cracks may have enhanced soil percolation and drying (Ritchie and Adams, 1974; Römkens and Prasad, 2006).

Monthly Available Soil-Water Storage Analyses

Measured monthly AWS at the study sites was less than 2 inches for the six sites, except for June–August 2017 at the Lynchburg Grass site, indicating that soils generally could hold less than 2 inches of water in 2 feet of soil (table 14). There seemed to be minor relations between measured monthly values of AWS and AWS values estimated using either PET or ET in the monthly water-balance equations at most of the study sites (table 14). Correlations were determined between measured monthly AWS and monthly AWS estimated using PET and ET to evaluate the strengths of the relations at each site. Linear regressions were performed on

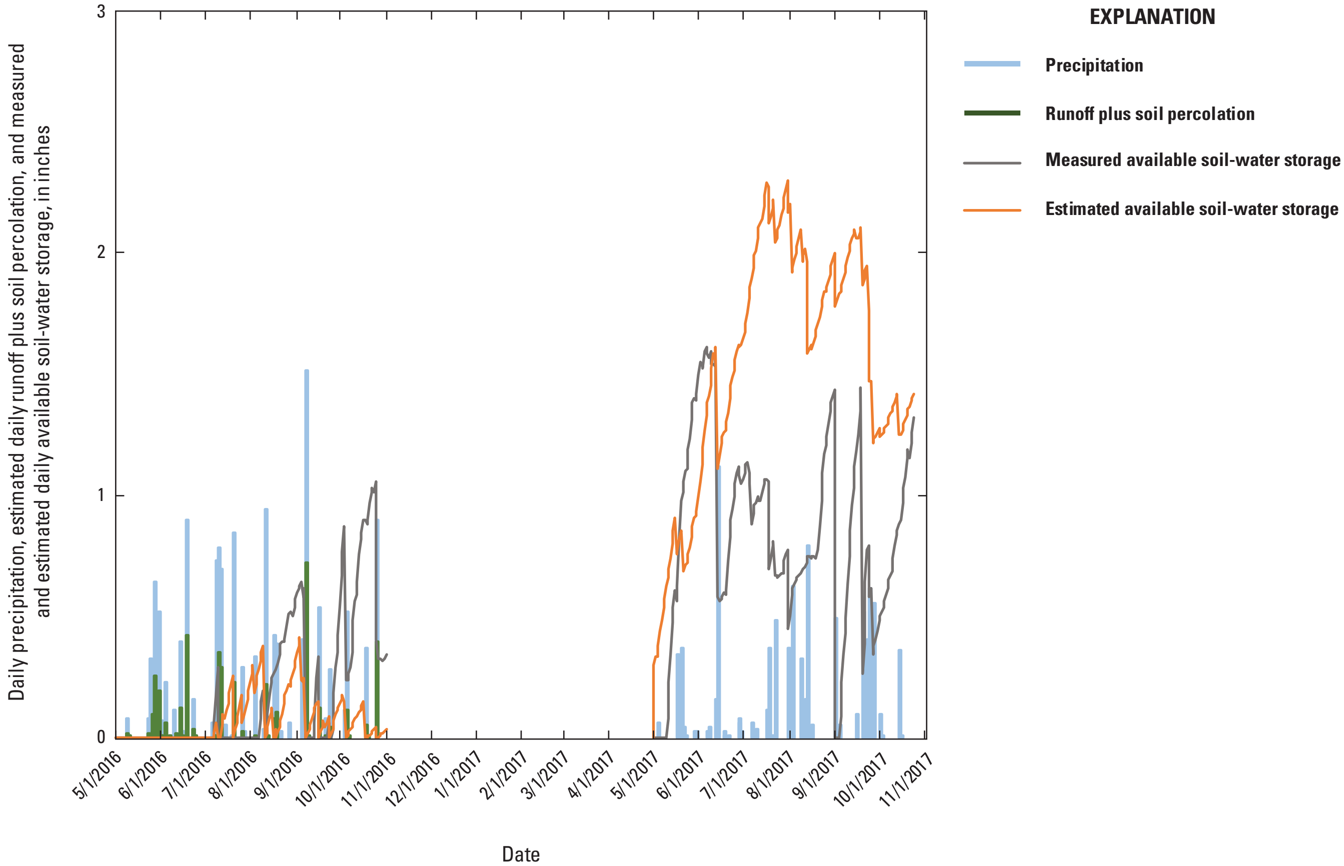


Figure 12. Daily precipitation, estimated runoff plus soil percolation, and measured and estimated daily available soil-water storage for May–October in 2016 and 2017 at the Lynchburg Crop study site in Cass County, North Dakota.

two groups of study sites, those with sandy soils (Brewer Lake, Embden East, Embden West, and Wills) and those with clay soils (Lynchburg Crop and Lynchburg Grass), to examine the relations between measured and estimated monthly AWS values for each soil type.

Monthly Available Soil-Water Storage for Sandy Soil Sites

Measured and estimated monthly AWS for the four sandy soil sites (Brewer Lake, Embden East, Embden West, and Wills) had large differences between measured values and values estimated using monthly PET and monthly ET in the monthly water-balance equations (table 14). Values of monthly AWS estimated using ET were zero at the four sandy soil sites during May 2016 and May 2017 likely because ET losses were estimated to be small (table 14). Correlation coefficients between measured AWS values and AWS values estimated using PET for 2016 and 2017 were greater than 0.4 at all sites except the Embden East site (table 15). Correlation coefficients between measured AWS values and AWS values estimated using ET for 2016 and 2017 (table 15) were greater than 0.4 at the Embden West site (0.72) and the Lynchburg Grass site (0.56).

Linear regressions were performed on measured monthly AWS values versus estimated monthly AWS values determined using monthly PET and monthly ET for the four sandy soil study sites grouped (fig. 15). Regression results indicated correlation coefficients of 0.62 and 0.56 between measured AWS values and values estimated using monthly PET and monthly ET, respectively. The slopes of the regression lines between estimated and measured monthly AWS using PET and using ET were 0.36 and 0.68, respectively. These results indicate little advantage using either monthly PET or monthly ET in water-balance equations to estimate monthly AWS for the grouped sandy soil study sites.

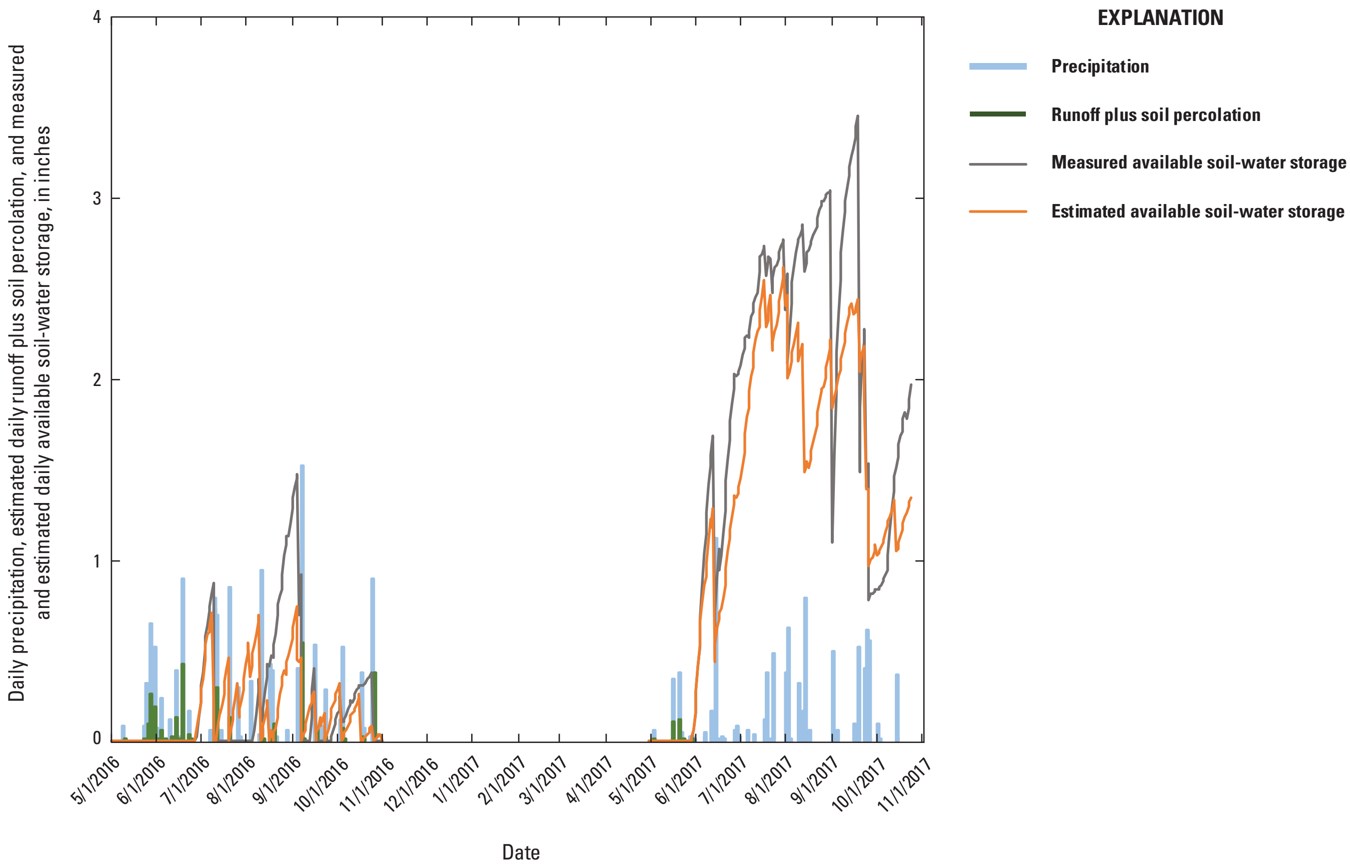


Figure 13. Daily precipitation, estimated runoff plus soil percolation, and measured and estimated daily available soil-water storage for May–October in 2016 and 2017 at the Lynchburg Grass study site in Cass County, North Dakota.

Monthly Available Soil-Water Storage for Clay Soil Sites

Measured and estimated monthly AWS for the clay soil sites had large differences between measured values and values estimated using monthly ET and monthly PET in the monthly water-balance equations (table 14). Values of monthly AWS estimated using ET were zero at both sites during May and June 2016 and at the Lynchburg Crop site in May and June 2017 (table 14). Measured monthly AWS at the Lynchburg Grass site exceeded 2 inches during June, July, and August 2017, likely because of cracks in the soil. Correlation coefficients between measured AWS values and AWS values estimated using PET for 2016 and 2017 were greater than 0.4 at the Lynchburg Crop site (0.48) and Lynchburg Grass site (0.85) and the correlation coefficient between measured AWS values and AWS values estimated using ET for 2016 and 2017 (table 15) was greater than 0.4 at the Lynchburg Grass site (0.56).

For the two grouped clay soil sites, linear regressions were performed on measured monthly AWS values versus estimated monthly AWS values determined using monthly PET and monthly ET (fig. 16). The regressions resulted in correlation coefficients of 0.73 and 0.47 between measured monthly AWS values and values estimated using PET and ET, respectively. The slopes of the regressions using PET and ET were 0.75 and 0.31, respectively. These results tend to indicate slightly better estimation of monthly AWS using monthly PET instead of monthly ET in water-balance equations for the grouped clay soil study sites.

Overall, the monthly water-balance models did not perform as well as the daily water-balance models for determining AWS at the six study sites. Results indicated slightly better estimation of monthly AWS using monthly PET instead of monthly ET in water-balance equations for the grouped clay soil study sites, but little advantage in the estimation of monthly AWS using using monthly PET or monthly ET in water-balance equations for the grouped sandy soil study sites. Information on AWS processes would seem to be obtained more readily using a daily time step; however, additional data collection from a longer-period study and adjustments to the models may improve results from the monthly water-balance techniques.

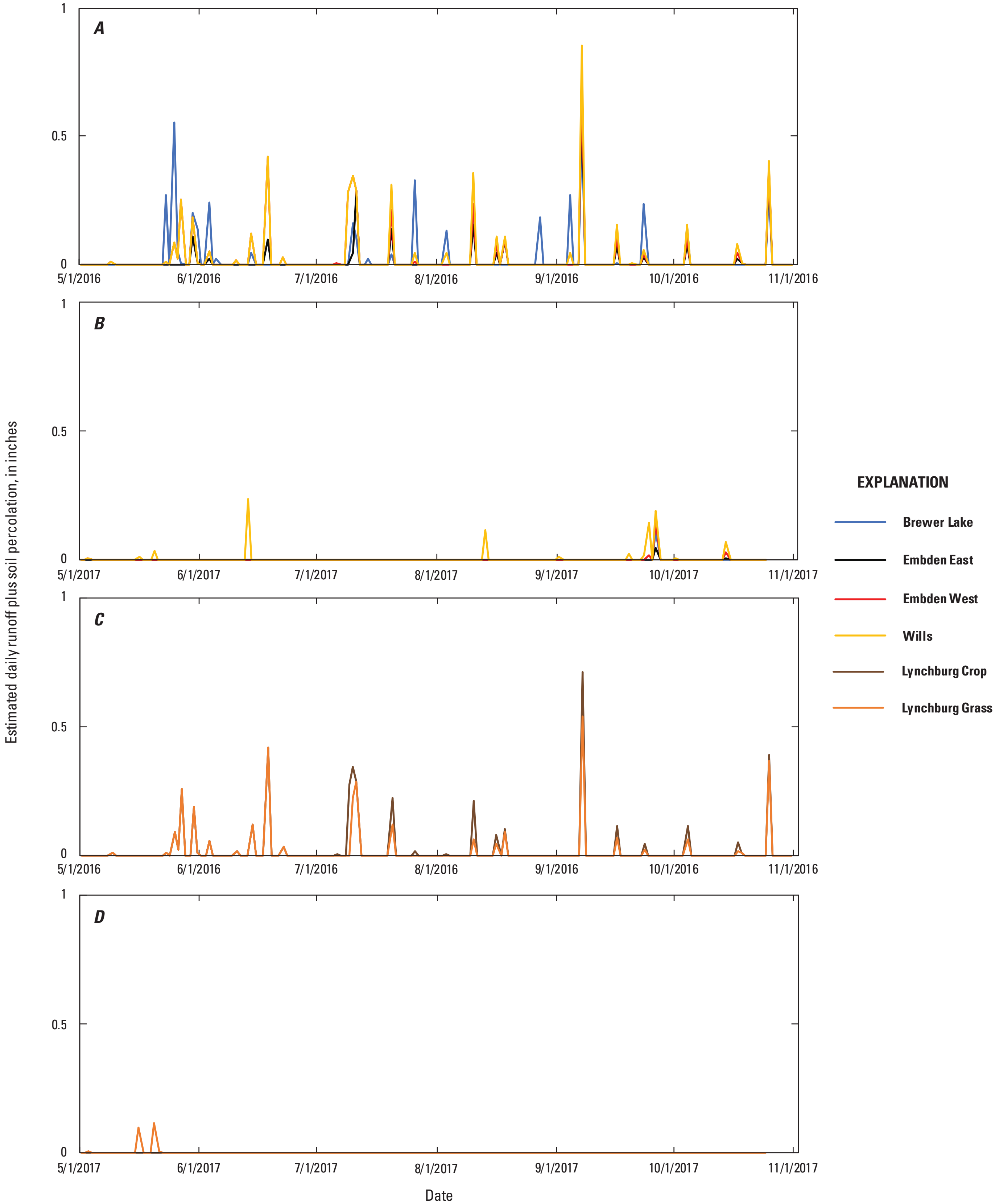


Figure 14. Estimated daily runoff plus soil percolation for the six study sites in Cass County, North Dakota. *A*, Brewer Lake, Embden East, Embden West, and Wills sites, May–October 2016. *B*, Brewer Lake, Embden East, Embden West, and Wills sites, May–October 2017. *C*, Lynchburg Crop and Lynchburg Grass sites, May–October 2016. *D*, Lynchburg Crop and Lynchburg Grass sites, May–October 2017.

Table 12. Monthly totals of daily runoff plus soil percolation, May–October means for the study sites, and mean runoff plus soil percolation for the grouped sandy soil sites and grouped clay soil sites in Cass County, North Dakota.

Month	Runoff plus soil percolation, in inches					
	Sandy soil study sites (fig. 1)				Clay soil study sites (fig. 1)	
	Brewer Lake	Embden East	Embden West	Wills	Lynchburg Crop	Lynchburg Grass
2016						
May	1.23	0.13	0.59	0.59	0.59	0.59
June	0.32	0.13	0.65	0.65	0.65	0.65
July	0.67	0.48	1.15	1.28	1.16	0.63
August	0.55	0.30	0.42	0.63	0.40	0.20
September	1.06	0.78	0.91	1.13	0.88	0.63
October	0.45	0.49	0.56	0.66	0.57	0.46
May–October	4.28	2.31	4.28	4.94	4.25	3.16
Group mean	3.95				3.71	
2017						
May	0.00	0.00	0.01	0.06	0.00	0.23
June	0.00	0.00	0.00	0.23	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.11	0.00	0.00
September	0.11	0.04	0.17	0.38	0.00	0.00
October	0.00	0.00	0.03	0.08	0.00	0.00
May–October	0.11	0.04	0.21	0.86	0.00	0.23
Group mean	0.31				0.12	

Table 13. Land cover, and precipitation, potential evapotranspiration, evapotranspiration, and mean estimated and measured daily available water-soil storage for May–October in 2016 and 2017 at the six study sites in Cass County, North Dakota.

[PET, potential evapotranspiration; ET, evapotranspiration, AWS, available soil-water storage]

Study site (fig. 1)	Year	Land cover	Values, in inches				
			Precipitation	PET	ET	Mean estimated daily AWS	Mean measured daily AWS
Brewer Lake	2016	Grass	16.98	35.98	17.99	0.16	0.37
	2017	Grass	10.27	38.23	11.93	1.21	0.76
Embden East	2016	Wheat	14.20	39.21	15.67	0.26	0.73
	2017	Corn	8.99	39.56	13.51	1.25	0.50
Embden West	2016	Wheat	14.20	39.21	15.67	0.07	0.11
	2017	Corn	8.99	39.56	13.51	0.73	0.42
Lynchburg Crop	2016	Sugar beets	14.20	39.21	15.67	0.07	0.18
	2017	Soybeans	8.99	39.56	10.00	1.53	0.83
Lynchburg Grass	2016	Grass	14.20	39.21	15.67	0.15	0.19
	2017	Grass	8.99	39.56	10.00	1.37	1.77
Wills	2016	Grass	14.20	39.21	15.24	0.03	0.01
	2017	Grass	8.99	39.56	12.76	0.31	0.36

Table 14. Monthly totals of precipitation, potential evapotranspiration, evapotranspiration, and runoff plus soil percolation; estimated available soil-water storage using potential evapotranspiration and evapotranspiration; and measured available soil-water storage for May–October in 2016 and 2017 at the six study sites in Cass County, North Dakota.

[PET, potential evapotranspiration; ET, evapotranspiration; AWS, available soil-water storage]

Month	Values, in inches						
	Precipitation	PET	ET	Runoff plus soil percolation	Estimated AWS using PET	Estimated AWS using ET	Measured AWS
				Brewer Lake			
May 2016	4.50	8.42	1.02	1.23	0.00	0.00	0.00
June 2016	1.79	7.85	2.44	0.32	0.15	0.02	0.71
July 2016	3.78	6.37	5.79	0.67	0.00	0.24	0.48
August 2016	2.43	6.29	4.69	0.55	0.00	0.67	0.73
September 2016	2.95	4.38	3.58	1.06	0.00	0.57	0.31
October 2016	1.53	2.68	0.47	0.45	0.00	0.10	0.05
May 2017	0.63	7.66	0.43	0.00	1.15	0.00	0.84
June 2017	2.03	8.67	2.56	0.00	1.27	0.00	0.91
July 2017	1.65	7.75	4.02	0.00	1.55	0.54	1.37
August 2017	0.87	5.87	3.66	0.00	2.06	1.30	0.85
September 2017	5.05	4.49	1.26	0.11	0.00	0.00	0.03
October 2017	0.04	3.80	0.00	0.00	0.60	0.00	0.58
				Embden East			
May 2016	1.86	8.94	0.00	0.13	0.16	0.00	0.00
June 2016	1.84	8.95	2.87	0.13	0.46	0.00	0.96
July 2016	3.49	7.31	6.06	0.48	0.00	0.00	1.55
August 2016	2.19	6.24	3.70	0.30	0.00	0.00	1.91
September 2016	2.85	4.74	3.03	0.78	0.00	0.00	0.66
October 2016	1.97	3.03	0.00	0.49	0.00	0.00	0.09
May 2017	0.87	8.20	0.31	0.00	0.90	0.00	0.36
June 2017	1.53	9.32	2.20	0.00	1.55	0.00	0.19
July 2017	1.44	8.11	4.49	0.00	2.03	0.79	1.26
August 2017	1.96	5.57	4.29	0.00	1.42	1.13	1.00
September 2017	2.72	4.72	2.09	0.04	0.00	0.08	0.01
October 2017	0.47	3.64	0.12	0.00	0.12	0.00	0.18
				Embden West			
May 2016	1.86	8.94	0.00	0.59	0.10	0.00	0.00
June 2016	1.84	8.95	2.87	0.65	0.35	0.00	0.00
July 2016	3.49	7.31	6.06	1.15	0.00	0.00	0.09
August 2016	2.19	6.24	3.70	0.42	0.00	0.00	0.72
September 2016	2.85	4.74	3.03	0.91	0.00	0.00	0.00
October 2016	1.97	3.03	0.00	0.56	0.00	0.00	0.00
May 2017	0.87	8.20	0.31	0.01	0.87	0.00	0.16
June 2017	1.53	9.32	2.20	0.00	1.48	0.00	0.04
July 2017	1.44	8.11	4.49	0.00	1.92	0.48	1.17
August 2017	1.96	5.57	4.29	0.00	1.25	0.59	0.63
September 2017	2.72	4.72	2.09	0.17	0.00	0.00	0.24
October 2017	0.47	3.64	0.12	0.03	0.10	0.00	0.43

Table 14. Monthly totals of precipitation, potential evapotranspiration, evapotranspiration, and runoff plus soil percolation; estimated available soil-water storage using potential evapotranspiration and evapotranspiration; and measured available soil-water storage for May–October in 2016 and 2017 at the six study sites in Cass County, North Dakota.—Continued

[PET, potential evapotranspiration; ET, evapotranspiration; AWS, available soil-water storage]

Month	Values, in inches						
	Precipitation	PET	ET	Runoff plus soil percolation	Estimated AWS using PET	Estimated AWS using ET	Measured AWS
Lynchburg Crop							
May 2016	1.86	8.94	0.00	0.59	0.41	0.00	0.00
June 2016	1.84	8.95	0.55	0.65	0.93	0.00	0.00
July 2016	3.49	7.31	6.69	1.16	0.28	0.58	0.00
August 2016	2.19	6.24	5.12	0.40	0.09	1.32	0.57
September 2016	2.85	4.74	3.31	0.88	0.00	0.93	0.53
October 2016	1.97	3.03	0.00	0.57	0.00	0.00	0.34
May 2017	0.87	8.20	0.20	0.00	0.83	0.00	1.49
June 2017	1.53	9.32	1.22	0.00	1.57	0.00	1.06
July 2017	1.44	8.11	3.82	0.00	2.17	0.66	0.45
August 2017	1.96	5.57	3.62	0.00	2.00	0.94	1.43
September 2017	2.72	4.72	1.14	0.00	1.20	0.00	0.48
October 2017	0.47	3.64	0.00	0.00	1.36	0.00	1.31
Lynchburg Grass							
May 2016	1.86	8.94	0.00	0.59	0.55	0.00	0.00
June 2016	1.84	8.95	0.55	0.65	1.22	0.00	0.21
July 2016	3.49	7.31	6.69	0.63	0.58	1.60	0.00
August 2016	2.19	6.24	5.12	0.20	0.44	3.07	1.28
September 2016	2.85	4.74	3.31	0.63	0.00	3.29	0.12
October 2016	1.97	3.03	0.00	0.46	0.00	2.31	0.00
May 2017	0.87	8.20	0.20	0.23	1.01	1.97	0.14
June 2017	1.53	9.32	1.22	0.00	1.94	1.82	2.04
July 2017	1.44	8.11	3.82	0.00	2.68	3.01	2.38
August 2017	1.96	5.57	3.62	0.00	2.56	3.84	3.04
September 2017	2.72	4.72	1.14	0.00	1.71	3.05	0.83
October 2017	0.47	3.64	0.00	0.00	1.92	2.81	1.96
Wills							
May 2016	1.86	8.94	0.00	0.59	0.00	0.00	0.00
June 2016	1.84	8.95	1.14	0.65	0.12	0.00	0.00
July 2016	3.49	7.31	6.18	1.28	0.00	0.00	0.02
August 2016	2.19	6.24	4.69	0.63	0.00	0.09	0.00
September 2016	2.85	4.74	3.23	1.13	0.00	0.00	0.00
October 2016	1.97	3.03	0.00	0.66	0.00	0.00	0.00
May 2017	0.87	8.20	0.16	0.06	0.75	0.00	0.42
June 2017	1.53	9.32	1.34	0.23	1.22	0.00	0.48
July 2017	1.44	8.11	4.41	0.00	1.53	0.46	0.33
August 2017	1.96	5.57	4.57	0.11	0.82	0.65	0.33
September 2017	2.72	4.72	2.28	0.38	0.00	0.00	0.20
October 2017	0.47	3.64	0.00	0.08	0.07	0.00	0.54

Table 15. Correlation coefficients between measured monthly available soil-water storage and estimated monthly available soil-water storage determined using potential evapotranspiration and evapotranspiration for the six study sites in Cass County, North Dakota.

[AWS, available soil-water storage; PET, potential evapotranspiration; ET, evapotranspiration]

Study site (fig. 1)	Correlation coefficient	
	Measured and estimated AWS using PET	Measured and estimated AWS using ET
Brewer Lake	0.75	0.37
Embden East	0.11	0.28
Embden West	0.53	0.72
Lynchburg Crop	0.48	0.02
Lynchburg Grass	0.85	0.56
Wills	0.64	0.26

Limitations

There are several limitations to determining soil AWS using soil volumetric water-content probes and associated water-balance methods. One limitation is that the process of installing probes disturbs the soil, so measurements may not represent the processes that are occurring in the surrounding undisturbed bulk soil. AWS is directly related to soil physical properties at the study sites such as soil type, soil dry bulk density, and possible soil cracking, which can affect the installation and operation of soil volumetric water-content probes and measurements of soil volumetric water content.

Another limitation is that the methods used to collect soil samples for determining soil gravimetric water content, soil dry bulk density, and soil volumetric water content could be affected by soil conditions. A sample from a wet soil may compress and stick to sampling equipment, whereas a sample from a dry soil may be hard to obtain or become overly fragmented. In addition, the published values of soil volumetric water content at field capacity and permanent wilting point, which were used for AWS determination, were mean values for the various soil types. Soils are rarely homogeneous, and actual field capacity and permanent wilting point volumetric water contents often vary horizontally depending on soil properties (Ward and Trimble, 2004).

In 2016, burrowing animals had a considerable affect at the Wills study site where two soil volumetric water-content probes were destroyed, and the soil at the site was severely disturbed. Also, in 2016, a layer of corn plant residue blew from an adjacent field onto a large area that included the study site. Within 2 months, most of the residue was removed by hand from the immediate study site but not from the surrounding area. Because of these incidents, all monitoring equipment at the Wills site was moved about 50 feet to the south of the original location in 2017. The presence of burrowing animals and plant residue may have affected results from the Wills study site. Changes in conditions at other study sites, such as soil cracking, may have resulted in collected data that may not fully represent the conditions of the areas surrounding the study sites.

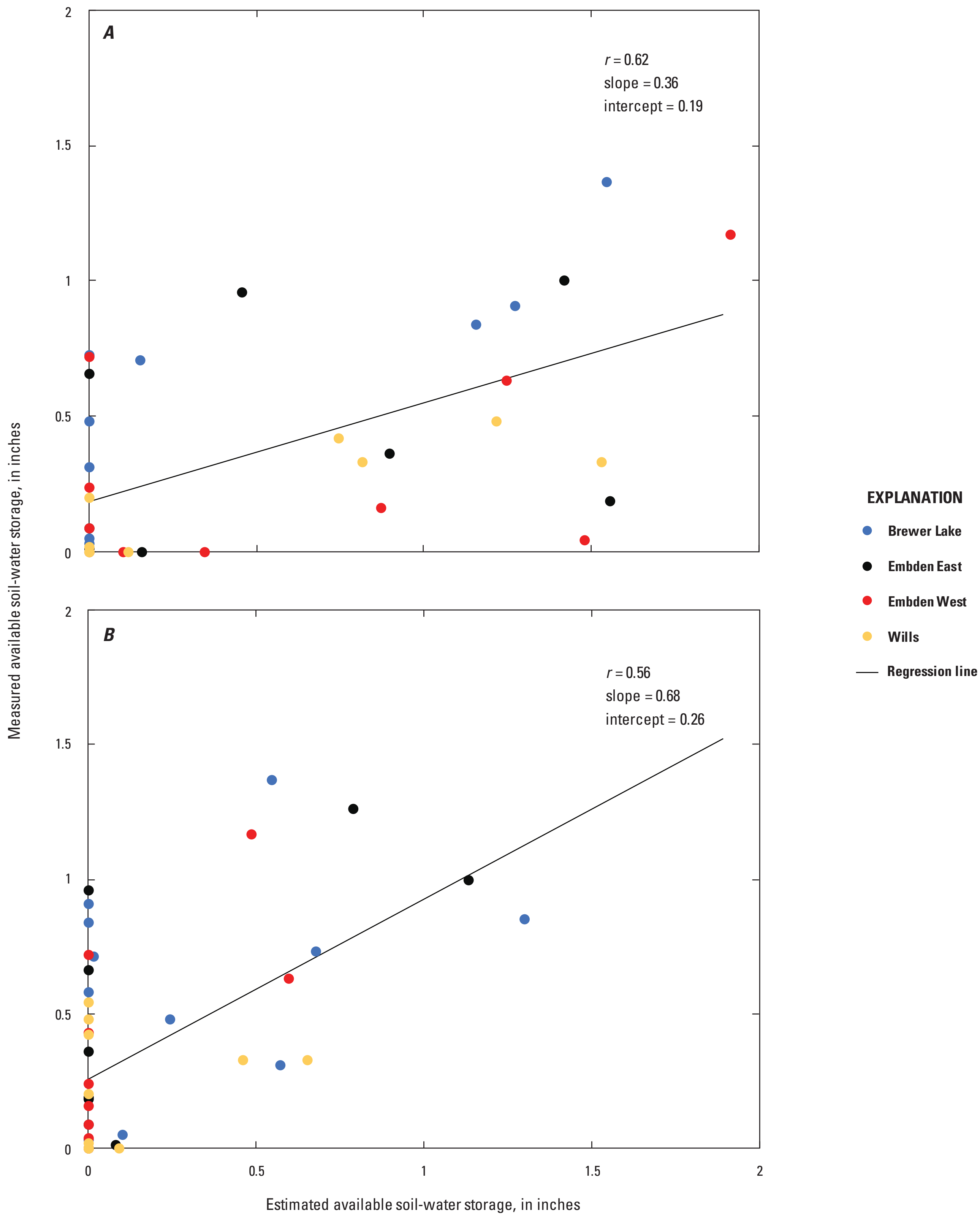


Figure 15. Regression of measured and estimated monthly available soil-water storage for May–October 2016 and 2017 for the grouped Brewer Lake, Embden East, Embden West, and Wills sandy soil study sites in Cass County, North Dakota. *A*, Monthly potential evapotranspiration used in calculations. *B*, Monthly evapotranspiration used in calculations.

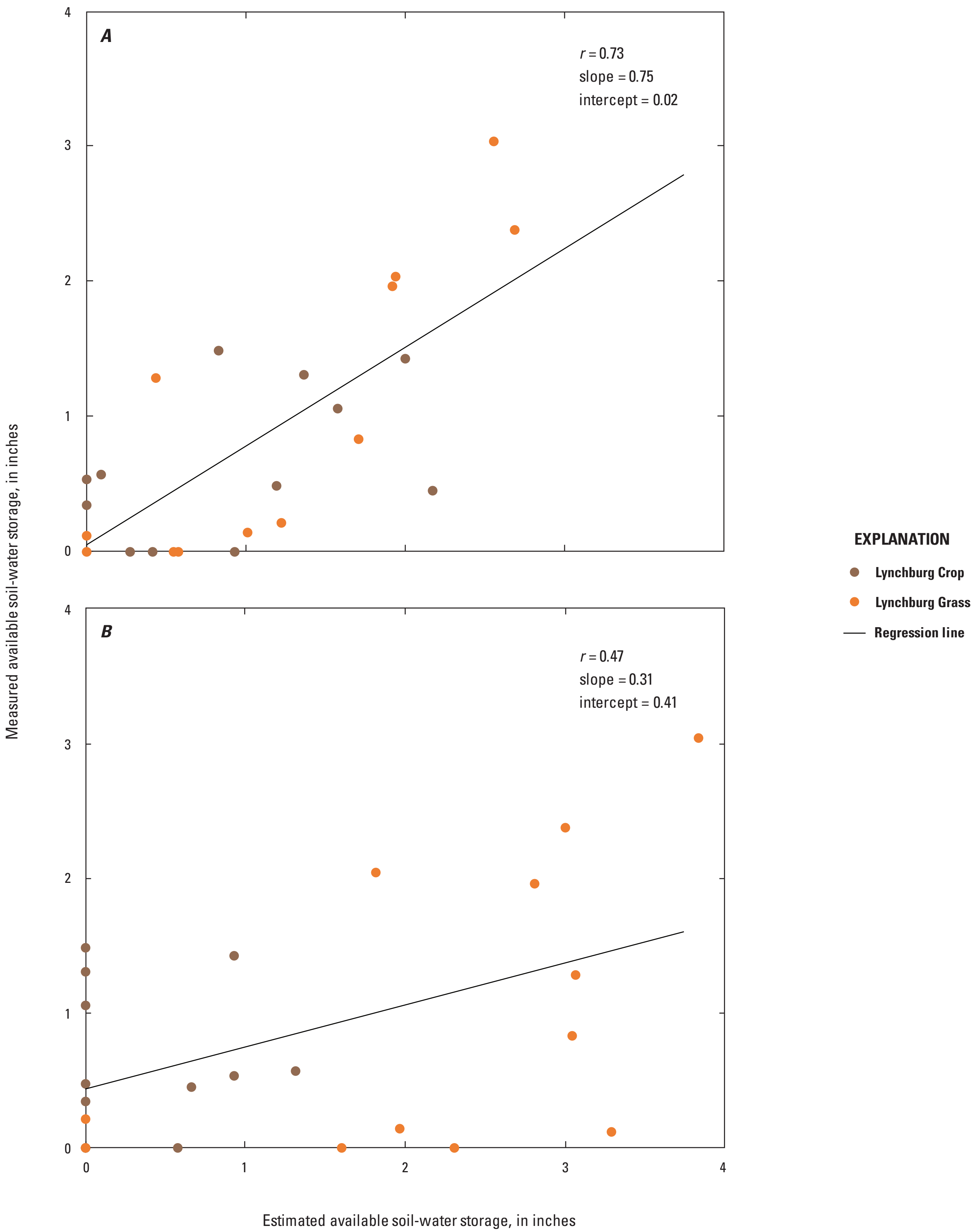


Figure 16. Regression of measured and estimated monthly available soil-water storage for May–October 2016 and 2017 for the grouped Lynchburg Crop and Lynchburg Grass clay soil study sites in Cass County, North Dakota. *A*, Monthly potential evapotranspiration used in calculations. *B*, Monthly evapotranspiration used in calculations.

Summary

The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Agriculture Natural Resources Conservation Service, collected field and remotely sensed precipitation, evapotranspiration, and soil-water content data on crop-production lands and nearby undisturbed grasslands to determine available soil-water storage (AWS) using basic water-balance techniques at six study sites on sandy soil types (Brewer Lake, Embden East and Embden West, and Wills) and clay soil types (Lynchburg Crop and Lynchburg Grass) in Cass County, North Dakota, to help inform conservation strategies. Data collected at the study sites included soil volumetric water-content data and soil physical data. Soil volumetric water-content data were collected hourly during May 1–June 16, 2016, and then every 15 minutes during June 17–October 31, 2016, and May 1–October 24, 2017, at all sites. Soil volumetric water-content data were reported as daily values using the last reading of each day. Precipitation and potentential evapotranspiration (PET) data that were used to estimate AWS were obtained from from nearby climate stations.

Monthly totals of evapotranspiration (ET) were estimated by personnel at the USGS Earth Resources Observation and Science center using satellite remote-sensing techniques and the Operational Simplified Surface Energy Balance model (SSEBop). The SSEBop model is a robust method that uses remotely sensed thermal data and weather information to produce ET estimates for the contiguous United States at monthly and seasonal time scales.

AWS during 2016 and 2017 was determined at daily and monthly time steps because of data availability and to assess results using varying time steps. Two values for daily and monthly AWS were determined and were referred to as "measured" and "estimated" values. Measured daily AWS was determined from daily soil volumetric water-content data and other soil physical data from the study sites. Estimated daily AWS was calculated from daily precipitation and PET data from the study sites and nearby climate stations that were used in water-balance equations. Measured monthly AWS was determined from aggregated daily soil volumetric water content. Estimated monthly AWS was calculated using two methods, the first using precipitation and PET data from the study sites and nearby climate stations, and the second using precipitation from the study sites and nearby climate stations and monthly ET data.

Runoff was not measured at the study sites, but runoff presumably occurred on some days from snowmelt during February and March 2017 and from rainfall during various other periods as indicated by the hydrographs of daily mean discharge for May 2016–October 2017 at USGS streamgages. Comparison of the flow volume for a period at a streamgage to the estimated runoff plus soil percolation volume for the contributing area of a streamgage will provide a fraction of runoff plus soil percolation that could be considered runoff. The remaining fraction of the runoff plus soil percolation could be considered soil percolation.

Measured monthly AWS values for each study site were determined as the end-of-month values from the measured daily AWS values for each study site. Estimations of monthly AWS used daily precipitation and PET data that were aggregated to monthly time steps and also used monthly ET data in water-balance techniques to evaluate the effect of PET and ET on AWS calculations. Monthly runoff plus soil percolation values for a study site could be more difficult to determine than on a daily basis because of the unknown pattern of precipitation that fell during a month, especially if only monthly data are accessible.

Comparisons of measured and estimated daily values of AWS at the Brewer Lake site indicated fair agreement during May–October 2016 and May–October 2017. Comparisons of measured and estimated daily values of AWS at the Embden East and Embden West sites indicated poor and fair agreement, respectively. The relation between estimated and measured AWS at the Wills site for May 2016 through October 2017 was good, but activity by burrowing animals destroyed two soil volumetric water-content probes, one at each depth, in late 2016, which resulted in relocation of the probes. At the Lynchburg Crop and Lynchburg Grass sites, comparisons of measured and estimated daily values of AWS indicated fair and good relations, respectively, even with the possible effects of soil cracks.

Mean estimated values of runoff plus soil percolation for the four sandy soil sites applied across the entire contributing drainage area for a nearby streamgage indicated that a maximum of about 19 percent of the estimated daily runoff plus soil percolation could be considered runoff to the river and that the remaining 81 percent could be considered soil percolation. If the mean estimated runoff plus soil percolation for the two clay soil sites was applied across the additional contributing drainage, then about 13 percent of the runoff plus soil percolation would have been considered runoff and about 87 percent would have been considered soil percolation. The topographic relief near the clay soil sites in central Cass County is very low, which can limit runoff.

Different crops grown in 2016 and 2017 at the Embden East and Embden West sites (wheat in 2016, corn in 2017) and at the Lynchburg Crop site (sugar beets in 2016, soybeans in 2017) may have affected AWS, but the lesser amounts of precipitation in 2017 than in 2016 also likely affected AWS. Values of PET, ET, and precipitation at the Lynchburg Crop and Lynchburg Grass sites were identical because of their proximity, but the differences in measured soil volumetric water contents at the sites may have resulted from distinct cracks that formed at the Lynchburg Grass site, which resulted in different equations to estimate daily AWS.

Measured and estimated monthly AWS for the six study sites had large differences between measured values and values estimated using monthly ET and monthly PET in the monthly water-balance equations. Results indicated

little difference between using monthly PET or monthly ET in water-balance equations to estimate monthly AWS for the grouped sandy soil sites, and only slightly better results using monthly PET than monthly ET to estimate monthly AWS for the grouped clay soil study sites. Overall, the monthly water-balance models did not perform as well as the daily water-balance models for determining AWS at the six study sites. Additional data collection from a longer-period study and adjustments to the models may improve results from the monthly water-balance techniques.

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