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physical properties of drought-hazard soils in central minnesota

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Foreword

This publication reports a study of the physical properties of drought-hazard soils (principally the Estherville series) in the Bonanza Valley area of central Minnesota. The investigation considers the soils' most common physical properties limiting the design and management of sprinkler systems for applying supplemental irrigation water during droughty periods.

This report is a joint contribution of the North Central Region of the Agricultural Research Service of the United States Department of Agriculture; the University of Minnesota Agricultural Experiment Station; the Soil Conservation Service; and the Pope and Stearns Soil and Water Conservation Districts.

The authors acknowledge the cooperation of land owners in the Bonanza Valley, the Soil Conservation Service personnel for their help in providing detailed soil profile descriptions and estimates of the investigation sites[1] available waterholding capacities, and the Agricultural Research Service technicians for collecting field data and soil samples and for analyzing soil samples.

Introduction

The presence and location of extensive shallow ground water aquifers under normally droughty or marginal farming areas boost the potential for irrigation development in Minnesota. Bonanza Valley, one area in central Minnesota where irrigation development is growing, encompasses about 200,000 acres northwest of Minneapolis along Minnesota Highway 55 between Paynesville and Glenwood.

The U.S. Geological Survey has already completed a study (1)[1] of the shallow aquifer resources under Bonanza Valley and is presently planning exploration of deeper aquifers in the area. The high quality water found in the annually recharged shallow aquifers assures extensive irrigation developments in the historically "drought hazard" areas. The Bonanza Valley area has a 130- to 140-day frost-free growing season suitable for most field crops and horticultural vegetable crops.

Estherville series soils, which cover over half (57 percent) Bonanza Valley, can best be described as a shallow soil with a 15- to 30-inch thick loamy mantle overlying coarse sands or gravels—a typically droughty soil formed in glacial outwash. Blake (2) and others have shown the potential severity of drought that can result on these soils having limited available water capacity. However with modern irrigation equipment, the drought hazard can be removed.

Planning and designing modern irrigation systems require knowledge of the physical properties of the soil to be irrigated. Two important properties pertinent to the design of modern sprinkler systems are the soil's available water capacity (AWC) and the sprinkler water intake rate. The AWC determines the maximum allowable irrigation frequency during rainless periods during the peak growing or crop water use season. The soil's maximum sprinkler water intake rate must be known to design mechanical moving sprinkler irrigation machines that can apply large amounts of water in relatively short periods of time.

The study was initiated in June 1971. Its objectives were to measure *in-situ* the available water capacity and sprinkler water intake characteristics of selected and representative field sites of predominant soils in central Minnesota having irrigation systems. The Soil Conservation Service and the Pope and Stearns County Soil and Water Conservation Districts cooperated in soil site selections, soil profile descriptions, and estimates of available water capacities of soil profiles. Twenty-four sites in the Bonanza Valley area (figure 1) were selected for onsite field measurements and investigations. The legal description of each site location is listed in Appendix A.

Methods used and data collected

General

An earlier method of measuring soils' field capacities and available water holding capacities required extracting cores of soil from fields, carefully transporting these cores to a laboratory, and conducting a series of water content measurements versus moisture tension. The main disadvantage was the relatively small soil samples obtained and the labor of acquiring cores and conducting measurements. Thereupon, measurement advanced to establishing empiri-

[1] Numbers in parentheses refer to a reference number under *References Cited.*

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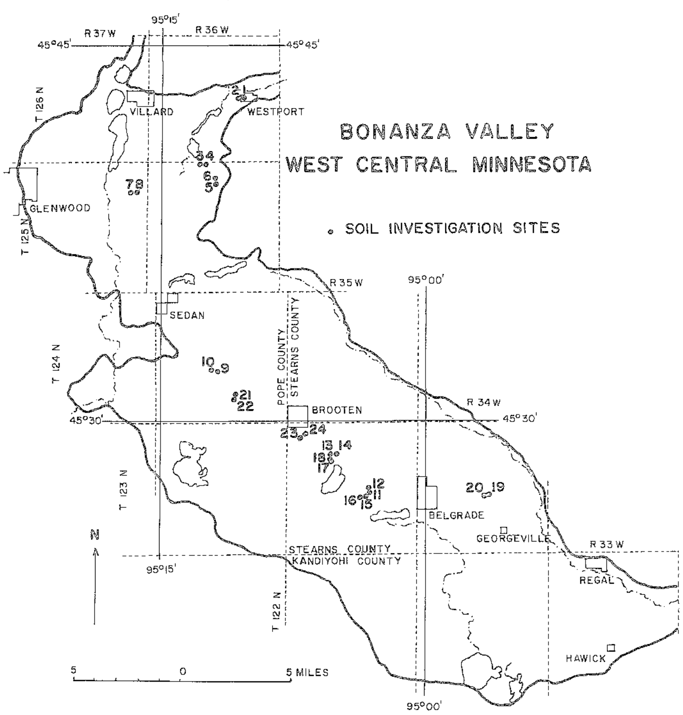
cal relationships between soil textures and their moisture storage characteristics.

The neutron probe instrument enabled measurement, in place, of the moisture content of relatively large soil profile samples (15 to 16 inches diameter) without significantly changing soil site conditions. This method also allowed repeated measurements of the same soil. Steel access tubes were driven into the gravelly soil profile with a specially hardened, fluted, pointed bar fitted inside the access tube and rotated between impacts from the driving hammer.

Measurements of the maximum sprinkler water intake versus time required a portable infiltrometer that could easily be transported and set up at the field site. A portable infiltrometer was designed and built that permitted rapid changes of the sprinkler application rate without momentary shutdowns. Using five nozzles of different sizes, each controlled by an individual valve, water could be applied at about any rate from 0.38 to 6.04 inches per hour. The water was applied to a 3 x 3-feet-square target area, and application rate adjustments were determined from visual observations of the wetted soil surface. Very slight ponding indicated too high an application rate. A dull-like, wetted soil surface appearing between intermittent passes of the nozzles indicated the application rate was less than intake.

At each of the sites, soil samples were collected for texture and organic matter content analysis. Bulk density was also measured for the top 12 inches of each soil profile in 6-inch increments. Soil Conservation Service personnel carefully examined the soil profiles and wrote complete profile descriptions for each site. All field and laboratory measurements of soils' physical properties were statistically analyzed for variability and inter-relationships.

Figure 1. Locations on soil investigation sites in the Bonanza Valley



Effective Field Capacity (EFC)

The field capacity (an obsolete technical term) (3) is the highest soil moisture level at which no appreciable drainage occurs. Determining a soil's field capacity generally required a laboratory measurement of the soil moisture content. This is done at some arbitrary moisture tension level where drainage has essentially ceased. Saturated noncropped soil profiles generally drain in about 2 to 6 days before reaching field capacity level. On a saturated, cropped soil profile, water lost to gravity drainage would be lessened by the amount used by growing crops during the drain-down period. Miller and Aastad (4) have shown that the evapotranspiration rate can significantly affect the amount of water above field capacity that a soil can hold for crop use.

Jensen (5) described this higher level of soil water content as the "effective field capacity" (EFC). He proposed a method to calculate it in the field from neutron measurements of drainage from saturated uncropped and insulated soil profiles. The method is based on the empirical, time-dependent drainage equation proposed by Ogata and Richards (6) in 1957:

$$W = W_0 \, t^{-m} \qquad [1]$$

W is the soil profile water content after drainage time, t, in days; W_0 is the soil profile water content on the day after saturation; and —m is an experimentally derived constant for a particular soil profile. The drainage rate expressed as a function of soil profile water content was further developed from equation [1].

$$\frac{dW}{dt} = -mW \left[\frac{W}{W_0} \right]^{1/m} \qquad [2]$$

Jensen proposed subtracting the daily evapotranspiration from the soil water content, W, in equation [2] before calculating the drainage rates for successive days. The cumulative drainage, W_D, from a cropped soil profile is thus calculated:

$$W_D = \sum_{i=1}^{\infty} m[W_{i-1} - (E_t)_i] \left[\frac{W_{i-1} - (E_t)_i}{W_0} \right]^{1/m} \qquad [3]$$

$[W_{i-1} - (E_t)_i]$ is the soil profile water content on the ith day after irrigation. Daily amounts of drainage water are calculated until dW/dt approaches 0. Subtracting the calculated drained water, W_D, from the measured water content, W_0, of a saturated noncropped profile estimates the effective field capacity. A higher estimate of the evapotranspiration rate E_t, in equation [3] results in a lower W_D, and possibly an overestimate of the EFC.

A 1½-inch diameter steel tube was installed at each soil site to a depth exceeding 36 inches. A 3-foot diameter metal dike was used to flood and saturate the soil profile around the tube. A calibrated neutron moisture gage measured the total soil profile moisture on the day following saturation for a measurement of W_0 and at 1- and 2-week intervals after saturation for calculating the drainage constant, m, in equation [1]. The W_0, m, and EFC values for two E_t rates were calculated for all 24 sites. These are tabulated in table 1.

Available Water Capacity

The available water capacity (AWC) is the difference in soil moisture content at field capacity and permanent wilting point. The permanent wilting point, M_{wp}, of a soil profile can be measured directly in the field with a neutron gage when the crop or vegetation shows severe moisture stress.

Measurements of the AWC on 10 preliminary field sites of Estherville sandy loam showed the AWC ranged from 0.5 to 0.62 of the EFC, with a mean of 0.54. Since the probability of summer rainfall in Minnesota was high, field sites were covered to exclude rainfall and to hasten soil moisture depletion to the M_{wp} level. Therefore, the AWC for the 24 sites was estimated at 0.5 EFC. The AWC for the 24 sites are tabulated in table 1.

Sprinkler Intake Rate

Normal irrigation practice is to apply water to crops when 40 to 60 percent of the available soil moisture supply has been used. Field studies at Westport in 1972 indicate that the 40 percent available soil profile moisture depletion level of the Estherville series soils was reached when the 9-inch depth tensiometers indicated 50 to 60 centibars soil moisture tension. Each site of sprinkler intake measurements was prepared by shielding and diverting rainfall with a translucent plastic canopy until tensiometers indicated soil moisture tensions of 50 to 60 centibars.

The plastic canopy was moved aside, and the portable infiltrometer was set up over the prepared site. Water was applied at the maximum rate without producing surface runoff. Application rates were increased or decreased when

Table 1. Effective field capacity and available water capacity determinations for 36-inch deep soil profiles at various sites in Bonanza Valley, Minn., in 1973

Site	W_o[1] (in.)	$-m$[1]	EFC[2] $E_t=$ 0.15 (in.)	EFC[2] $E_t=$ 0.25 (in.)	AWC[3] (in.)
1	12.49	0.0430	11.76	11.96	5.9
2	9.41	.0658	8.54	8.77	4.3
3	8.20	.0567	7.64	7.81	3.8
4	9.78	.0714	8.75	9.00	4.4
5	8.77	.0873	7.63	7.90	3.8
6	7.38	.0912	6.44	6.68	3.2
7	9.58	.0706	8.60	8.84	4.3
8	10.03	.0511	9.36	9.55	4.7
9	9.77	.0554	9.05	9.25	4.5
10	9.02	.0425	8.60	8.74	4.3
11	9.69	.0856	8.41	8.69	4.2
12	9.82	.0834	8.55	8.84	4.3
13	7.98	.0795	7.10	7.33	3.6
14	10.60	.0757	9.35	9.63	4.7
15	7.98	.0737	7.19	7.40	3.6
16	8.79	.0751	7.85	8.09	3.9
17	9.22	.0547	8.57	8.76	4.3
18	6.97	.0536	6.57	6.71	3.3
19	8.64	.0841	7.58	7.83	3.8
20	8.22	.0641	7.54	7.73	3.8
21	9.41	.1193	7.57	7.92	3.8
22	8.74	.0982	7.42	7.71	3.7
23	7.96	.0536	7.46	7.62	3.7
24	10.21	.0499	9.55	9.74	4.8

[1] W_o and $-m$ are empirical values for equation [1]: $W = W_o t^{-m}$.

[2] EFC are calculated for two evapotranspiration rates: $E_t = 0.15$ and $E_t = 0.25$ inch per day.

[3] AWC $\cong$ 0.5 EFC.

Table 2. Summary of parameters calculated from cumulative sprinkler water intake versus time measurements made at 24 sites in Bonanza Valley, Minn., in 1973

Site	A[1]	n[1]	c[2]	Correlation R[3]	SE[3] estimate (in.)
1	0.066	0.944		0.9992	0.0702
2	.116	.675		.9897	.1044
2	.799	.298	−0.957	.9978	.0448
3	.083	.823		.9999	.0173
4	.119	.754		.9993	.0572
5	.146	.740		.9993	.0587
6	.112	.738		.9998	.0194
7	.072	.951		.9998	.0391
8	.077	.843		.9998	.0313
9	.096	.792		.9986	.0551
10	.083	.844		.9991	.0595
11	.058	1.111		.9994	.0855
12	.066	.968		.9994	.0733
13	.095	.835		.9984	.0674
14	.068	.995		1.0000	.0117
15	.080	.851		.9994	.0441
16	.103	.769		.9994	.0453
16	.155	.684	−0.129	1.0000	.0113
17	.066	.903		.9986	.0769
18	.057	.990		.9994	.0796
19	.081	.856		.9971	.0840
19	.273	.582	−0.382	.9978	.0726
20	.113	.738		.9994	.0312
21	.135	.608		.9947	.0610
22	.061	.803		.9965	.0785
22	.176	.594	−0.320	.9997	.0236
23	.096	.701		.9991	.0356
24	.092	.698		.9989	.0335

[1] $W = A t^n$, where W is inches water depth, t is cumulative time in minutes, and A and n are empirical constants. Site values for A and n can also be used to solve equation [5]:

$$\frac{dW}{dt} = n A t^{n-1}.$$

[2] For equation: $W = A t^n + c$. A modified equation form that allows slightly better fit of the experimental data from the same numbered site.

[3] Statistical correlation R, and standard error of estimate of the calculated equation [4] and experimental data for each site.

visual observations indicated a need. Analysis of the sprinkler water intake measurements showed that the cumulative water intake equation followed:

$$W = A\ t^{n} \qquad [4]$$

where W and t are cumulative inches of sprinkler water intake and the elapsed time in minutes, respectively, and A and n are empirical constants for each soil site. The A and n values were determined by linear regression analysis:

$$\log W = \log A + n \log t$$

where log A and n are the y-intercept and slope coefficient of the linear equation. Table 2 is the empirical constants, A and n, for the cumulative water intake equation [4] for each site.

The sprinkler water intake rate for any point of time in equation [4] can be calculated from:

$$\frac{dW}{dt} = n A t^{n-1} \qquad [5]$$

where $\frac{dW}{dt}$ is the sprinkler intake rate in inches per minute, t is the minutes time after start of sprinkler irrigation, and n and A are empirical constants related to site conditions.

Soil Profile Properties

Soil profile samples from each site were analyzed in the laboratory for a textural determination according to the USDA Textural Classification Guide (7). The gravel portion (diameter > 2 mm) of the air-dried soil sample was sieved, weighed, and expressed as a percentage of the total sample weight. The sand, silt, and clay fractions were determined by the hydrometer method (8, 9) and expressed as a percentage of the combined sand, silt, and clay portion.

The organic matter content of the loams and sandy loams was determined by oxidizing with a 30 percent hydrogen peroxide solution (10).

The bulk density of 0- to 6- and 6- to 12-inch increments of soil profile depths was determined by weighing air-dried soil volume samples.

Results of the soil texture, organic matter content, bulk density, and soil reaction (pH) determinations for each soil profile are listed in Appendix B. Soil profile descriptions for each of the 24 sites were prepared by Soil Conservation Service soil scientists and are detailed in Appendix C. SCS soil scientists also estimated the available water capacity (AWC based on soil profile textures and organic matter content) for 36-inch depth soil profiles at each site. Table 3 compares AWC values based on soil profile textures and AWC values calculated from neutron gage measurements of "effective field capacity" (AWC = 0.5 EFC).

Data analysis and significance

Effective Field Capacity (EFC)

Assuming the 24 selected sites are representative of the drought-hazard Estherville soils in the Bonanza Valley, some statistical determinations can be made about the EFC measurements. The average or mean EFC (for $E_t = 0.15$ inch per day) for 24 sites was 8.22 inches. The standard deviation, S_x, of the EFC measurements was 1.14 inches. Based on the variance of the EFC measurements for the 24 sites, the 95 percent confidence intervals indicate the true mean to be between 7.74 and 8.70 inches.

Table 3. Available water capacities of 36-inch soil profiles in Bonanza Valley, Minn.

Site No.	AWC = 0.5 EFC (in.)	AWC[1] (in.)
1	5.9	6.12
2	4.3	3.79
3	3.8	3.71
4	4.4	3.64
5	3.8	3.80
6	3.2	4.50
7	4.3	4.84
8	4.7	4.70
9	4.5	3.53
10	4.3	3.99
11	4.2	3.05 (2.7-3.4)[2]
12	4.3	4.15 (3.7-4.6)
13	3.6	4.65 (4.2-5.1)
14	4.7	4.95 (4.6-5.3)
15	3.6	4.05 (3.7-4.4)
16	3.9	4.95 (4.6-5.3)
17	4.3	3.45 (3.1-3.8)
18	3.3	2.70 (2.4-3.1)
19	3.8	4.95 (4.2-4.9)
20	3.8	3.55 (3.2-3.9)
21	3.8	5.24
22	3.7	3.34
23	3.7	3.6 (3.2-4.0)
24	4.8	4.25 (3.9-4.6)
Average	4.11	4.15

[1] Estimates for 36-inch depth soil profiles by SCS soil scientists (based on soil texture and O.M. content).
[2] An estimate of the AWC range was provided. The median of the range was used for statistical comparisons.

Available Water Capacity (AWC)

A soil profile's AWC is its moisture content difference between the field capacity level and the permanent wilting point. Empirical relationships reduce the labor and time required to estimate AWC. Two methods were used to estimate AWC of the 36-inch depth soil profiles at 24 sites. The first method is based on the relationship AWC = 0.5 EFC, where the EFC is calculated from soil profile moisture measurements with the neutron gage. A second method (used by SCS) bases the AWC estimate on soil texture and organic matter content measurements of soil profile samples. Soil Conservation Service soil scientists for Pope and Stearns County Soil and Water Conservation Districts prepared AWC estimates for each of the 24 investigation sites. The statistical parameters for the two methods of estimating AWC for the 24 sites are shown in table 4. Calculating the difference in AWC at each site by the method of measurements permits applying the "students" t-test for paired observations (11). The results show no significant difference in the estimate of AWC by the two methods (table 4).

Table 4. Comparison of AWC values for 24 sites in Bonanza Valley as determined by different methods

	AWC (0.5 EFC)	AWC (based on texture analysis)
Observations	24	24
Sample mean, $\bar{X}$	4.11 inches	4.15 inches
Standard Dev., S_x	0.577 inches	0.791 inches
95% CI*	3.11 to 5.11	2.76 to 5.54

* 95 percent confidence intervals that would contain true population mean.

Sprinkler Intake Rate

The cumulative water intake generally follow equation [4]; however, a modified equation, $W = A\ t^n + c$, improved correlation R and provided an equation with smaller standard error of estimate, SE, for four of the sites.

An equation calculated for the data pooled from all 24 sites follows the form of equation [4] and is:

$$W = 0.0892\ t^{0.830} \qquad [6]$$

where W is the cumulative inches of water intake and t is the sprinkler irrigation time in minutes. The average intake rate, $\frac{dW}{dt}$, in inches per hour for, t, the minutes of time after start of sprinkling for all 24 sites follows the form of equation [5] and is:

$$\frac{dW}{dt} = 4.44 t^{-0.170} \qquad [7]$$

Equations [6] and [7] are average for the 24 sites. The statistical mean and standard deviation of the calculated A values for all 24 sites (table 2) are 0.0892 and 0.0246 inches, respectively. The statistical mean and standard deviation of calculated n values for all sites (table 2) are 0.830 and 0.120. Figure 2 shows the plot of cumulative intakes and intake rates versus time for equations [6] and [7].

The variability of sprinkler water intake at each site is attributed to experimental error and site conditions. Four physical properties of soil site conditions were considered for multiple regression analysis. Values of water intake, W, in equation [4] for each site were the dependent variables; the percentage of silt, clay, organic matter, and the bulk densities of the top 6-inch soil layer were the independent variables. The highest multiple correlation coefficient, R = 0.54, was obtained for dependent variable values of the longest time intervals (t = 90 minutes). All multiple correlation coefficients calculated from dependent variables of shorter times were lower. The independent variables, bulk density and percentage of clay, showed the highest correlation of linear regression with the dependent

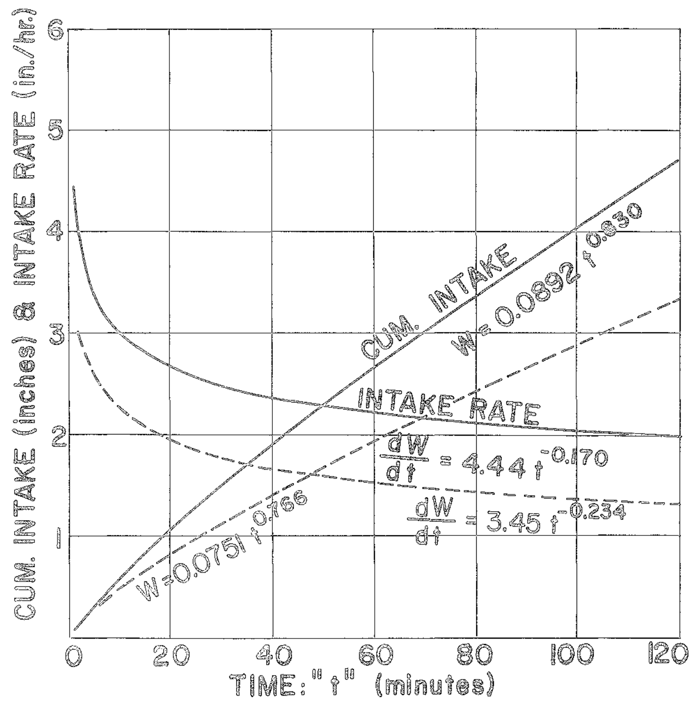


Figure 2. Cumulative intakes and intake rates vs. elapsed time equation for pooled field measurement data from 24 sites in the Bonanza Valley. Broken line curves are for equations developed from the 99 percent confidence interval (lower) of the mean for the 24 sites.

variable, W; however, both would be rejected if the rigorous 0.01 and 0.05 levels of significance were applied.

Multiple linear regression analysis was performed for the same four independent variables with the calculated values of A and n in the cumulative water intake equation [4] for each site designated as the dependent variables. The multiple correlation coefficient for linear regression for the two dependent variables A and n was 0.48 and 0.59, respectively. The percentage of clay showed a significant correlation of linear regression at the 0.05 statistical level with both dependent variables.

Comments and conclusions

To design irrigation systems, estimates are needed of the available water capacity of shallow soils underlain with medium and coarse sands and gravels. By using a neutron gage to measure soil moisture in an essentially undisturbed soil profile in the field, effective field capacities (EFC) of the shallow Estherville soils were calculated by an equation accounting for the evapotranspiration rate after saturation. Values of the available water capacities (AWC) for each site were then calculated from the EFC amounts. Independent estimates of the AWC for each site by Soil Conservation Service soil scientists (based on thickness and texture analysis of the significant layers) showed remarkably good agreement with the AWC values calculated from EFC measurements using the neutron probe (table 3). The 95 percent statistical confidence intervals that would contain the true population mean AWC for the drought hazard soils in Bonanza Valley was 3.11 to 5.11 inches for one method and 2.76 to 5.54 inches for the other.

The cumulative sprinkler water intake verus time for the shallow Bonanza Valley soils was described by an equation of the form: $W = A t^n$. Although the sprinkler infiltrometer could easily be controlled to apply water at any rate between 0.38 and 6.04 inches per hour, water intake was not correlated with other measured soil parameters which indicated experimental error and/or poor selection of independent soil variables. Other investigators (12, 13) have shown that surface seals can significantly affect infiltration or intake rate. This aspect was not studied in this general soils investigation and may be a prime source of error in correlating rate to soil properties.

The average cumulative intake versus time and the average intake rate versus time (figure 2) might seem useful for design purposes. However, the measurement data is from only 24 sites. Equations calculated from the lower 99 percent confidence limit of the "A" and "n" parameter values for the 24 sites are represented by broken lines in figure 2. When verified onsite intake rates are unknown, these equations would be safer to use and should represent the maximum design rate for Estherville and related series soils. To estimate potential surface runoff amounts, Kincaid and others (14) have related the application rate hydrograph of center-pivot irrigation systems to the soils' measured sprinkler water intake rate function. To minimize surface water runoffs, similar procedures could be applied to design moving gun and moving rotating-boom systems. Presently, there are insufficient measurments of the application hydrographs from the latter two systems.

We recommend that 1 to 1.25 inches of irrigation water be applied whenever 50 percent of the available soil moisture in Estherville soils has been depleted. This represents about a 50 percent replenishment of the average soil moisture depletion. We conjecture that the danger of deep percolation and fertilizer leaching losses could be substantially reduced through such management. Lysimeter studies are underway at Westport to determine the reduction of deep percolation and fertilizer leaching losses resulting from such irrigation water management compared to irrigating to replenish 100 percent of the soil moisture deficit.

References cited

1. Van Voast, W. A. 1971. "Ground Water for Irrigation in the Brooten-Belgrade Area, West-Central Minsota," Geological Survey Water-Supply Paper 1899-E USDI, Geological Survey, Water Resources Division, U.S. Government Printing Office, Washington, D.C.
2. Blake, G. R., E. R. Allred, C. H. M. van Bavel, and F. D. Whisler. 1960. "Agricultural Drought and Moisture Excesses in Minnesota" Univ. of Minn. Tech. Bl. 235, May.
3. Soil Science Society of America Proceedings. 1965. Glossary of Soil Science Terms. Soil Sci. Soc. Amer. Proc. 29:330-351.
4. Miller, D. E., and J. S. Aastad. 1971. "Available Water as Related to Evapotranspiration Rates and Deep Drainage," Soil Sci. Soc. Amer. Proc. 35:1:131-134.
5. Jensen, M. E. 1972. "Programming Irrigation for Greater Efficiency," *Optimizing Soil Physical Environment Toward Greater Crop Yields,* Academic Press, Inc., New York and London. pp. 153-155.
6. Ogata, G., and L. A. Richards. 1957. "Water Content Changes Following Irrigation of Bare-Field Soil that is Protected from Evaporation," Soil Sci. Soc. Amer. Proc. 21:4:355-356.
7. USDA. 1948. *Soil Textural Classification Guide*. Bureau of Plant Industry and Agricultural Engineering. March 17.
8. Day, P. R. 1956. "Report of Committee on Physical Analyses," Soil Sci. Soc. Amer. Proc. 20:167-169.
9. Day, P. R. 1950. "Physical Basis of Size Analyses by the Hydrometer Method," Soil Science 70:363-374.
10. USDA. 1954. *Agricultural Handbook 60*, p. 123, February.
11. Ostle, Bernard. 1960. *Statistics in Research.* Iowa State University Press.
12. Hanks, R. J. 1965. "Estimating Infiltration from Soil Moisture Properties," J. Soil and Water Conserv. 20:2:49-51. March-April.
13. Edwards, William M., and W. E. Larson. 1969. "Infiltration of Water into Soils as Influenced by Surface Seal Development," Trans. of the ASAE 12:4:463-465, 470.
14. Kincaid, D. C., D. F. Heerman, and E. G. Kruse. 1969. "Application Rates and Runoff in Center-Pivot Sprinkler Irrigation" Trans. of the ASAE 12:6:790-794, 797.

APPENDIX A. Locations of drought-hazard soil sites investigated in Bonanza Valley in 1973

Site no.	County	Legal description (nearest 10-acre)
1	Pope	T126N-R36W-Sec. 23, NW_{160}, NE_{40}, NE_{10}
2	Pope	T126N-R36W-Sec. 23, NW_{160}, NE_{40}, NW_{10}
3	Pope	T125N-R36W-Sec. 4, NW_{160}, NE_{40}, NW_{10}
4	Pope	T125N-R36W-Sec. 4, NW_{160}, NE_{40}, NE_{10}
5	Pope	T125N-R36W-Sec. 3, NW_{160}, SW_{40}, SW_{10}
6	Pope	T125N-R36W-Sec. 3, NW_{160}, SW_{40}, NW_{10}
7	Pope	T125N-R37W-Sec. 12, NW_{160}, SW_{40}, SW_{10}
8	Pope	T125N-R37W-Sec. 12, NW_{160}, SW_{40}, SW_{10}
9	Pope	T124N, R36W-Sec. 21, SE_{160}, NE_{40}, NW_{10}
10	Pope	T124N-R36W-Sec. 21, SE_{160}, NE_{40}, NW_{10}
11	Stearns	T123N-R35W-Sec. 22, NE_{160}, NE_{40}, NW_{10}
12	Stearns	T123N-R35W-Sec. 22, NE_{160}, NE_{40}, NW_{10}
13	Stearns	T123N-R35W-Sec. 9, SW_{160}, NW_{40}, NW_{10}
14	Stearns	T123N-R35W-Sec. 9, SW_{160}, NW_{40}, NW_{10}
15	Stearns	T123N-R35W-Sec. 22, NE_{160}, SW_{40}, SE_{10}
16	Stearns	T123N-R35W-Sec. 22, NE_{160}, SW_{40}, SW_{10}
17	Stearns	T123N-R35W-Sec. 9, SW_{160}, SW_{40}, NW_{10}
18	Stearns	T123N-R35W-Sec. 9, SW_{160}, SW_{40}, NW_{10}
19	Stearns	T123N-R34W-Sec. 22, SW_{160}, NE_{40}, NE_{10}
20	Stearns	T123N-R34W-Sec. 22, SW_{160}, NE_{40}, NE_{10}
21	Pope	T124N-R36W-Sec. 27, SE_{160}, SW_{40}, SE_{10}
22	Pope	T124N-R36W-Sec. 27, SE_{160}, SW_{40}, SE_{10}
23	Stearns	T123N-R35W-Sec. 6, SE_{160}, NW_{40}, NW_{10}
24	Stearns	T123N-R35W-Sec. 6, SE_{160}, NW_{40}, NE_{10}

APPENDIX B. Summary of textural properties of Bonanza Valley soil profiles

Site no.	Profile depth (in.)	Gravel [1]	Sand [2]	Silt [2]	Clay [2]	O.M. [3]	B.D. [4]	pH	Textural class [5]
1	0-6	0.2	40.4	38.4	21.2	8.0	0.84	4.9	L
	6-12	5.9	53.6	25.8	20.5	4.0	1.20	4.8	SCL
	12-26	3.6	59.8	19.4	20.8	0.7		5.5	SCL
2	0-6	0.8	57.9	23.8	18.3	3.6	1.30	5.0	SL
	6-12	8.0	69.0	16.8	14.1	1.1	1.71	5.4	SL
	12-15	5.4	66.8	16.1	17.1	0.7		5.9	SL
	15-21	46.0	78.3	8.0	13.7	0.7		6.0	GSL
3	0-6	0.9	68.9	17.4	13.7	3.1	1.20	5.1	SL
	6-12	14.5	75.8	9.1	15.1	1.1	1.82	5.3	SL
	13-18	36.1	85.3	4.7	10.0	0.5		6.0	GLS
	18-24	22.9	87.5	4.5	8.0	–		7.4	GLS
	24-27	45.4	87.2	3.8	9.0	–		7.7	GLS
4	0-6	0.3	59.7	24.5	15.8	5.2	1.09	4.9	SL
	6-12	3.6	62.6	18.8	18.6	2.3	1.42	5.2	SL
	10-15	3.3	68.2	14.5	17.2	0.9		6.6	SL
	15-23	19.0	86.3	3.1	10.5	0.2		7.0	SL
5	0-6	0.6	62.1	18.6	19.3	2.8	1.31	5.0	SL
	6-12	3.0	62.3	19.6	18.1	2.2	1.58	5.1	SL
	16-21	28.3	88.6	2.5	8.9	1.1		6.3	GLS
	21-24	48.6	87.1	5.1	7.8	1.2		7.2	GLS
6	0-6	0.7	67.5	15.3	17.1	2.3	1.49	4.8	SL
	6-12	6.3	76.3	8.0	15.6	0.6	1.81	5.2	SL
	13-17	5.4	86.5	2.5	11.0	0.2		6.0	LS
	17-26	5.8	89.8	0.5	9.6	–		6.3	LS
7	0-6	0.7	52.1	31.9	15.9	6.7	0.88	6.2	SL
	6-12	3.1	62.0	21.8	16.2	3.0	1.33	5.9	SL
	11-19	0.5	53.5	26.0	20.4	1.1		5.6	SCL
	19-24	11.6	56.9	23.3	19.8	0.6		5.6	SL
	24-32	31.2	83.0	6.7	10.3	0.3		6.1	GLS
	32-36	51.4	86.2	4.5	9.3	–		7.3	GLS
8	0-6	1.1	48.9	32.2	18.9	4.3	0.83	5.4	L
	6-12	0.4	43.1	32.9	24.0	2.4	1.29	5.2	L
	10-17	4.3	51.1	26.1	22.8	0.9		5.9	SCL
	17-21	59.4	84.0	8.6	7.4	1.5		7.4	GLS
9	0-6	0.4	62.1	22.3	15.7	2.8	1.17	5.0	SL
	6-12	0.4	56.5	24.8	18.7	1.2	1.51	5.2	SL
10	0-6	0.7	66.9	18.5	14.6	2.5	1.45	5.1	SL
	6-12	0.6	54.8	26.0	19.2	1.4	1.43	5.1	SL
	12-18	1.7	50.3	27.9	21.8	1.3		6.1	SCL
	18-26	27.5	89.4	2.6	8.0	–		6.5	GS

[1] Gravel as a percentage of total sample by weight.

[2] Reported as a percentage of the sand, silt, plus clay fraction.

[3] Organic matter content as a percentage of the sand, silt, plus clay fraction.

[4] Bulk density as grams weight per cubic centimeter volume.

[5] S—sand or sandy; C—clay; L—loam or loamy; G—gravelly (gravel content is 20% or more of the total sample). VG—very gravelly (gravel content more than 60% of total sample by weight). The hydrometer method of particle-size analysis does not distinguish between various subclasses of sands and sandy loams; for example, coarse sandy loam, fine sandy loam, and very fine sandy loam. Refer to the descriptions for the field estimate of these subclasses.

APPENDIX B. Summary of textural properties of Bonanza Valley soil profiles

Site no.	Profile depth (in.)	Gravel [1]	Sand [2]	Silt [2]	Clay [2]	O.M. [3]	B.D. [4]	pH	Textural class [5]
11	0-6	0.3	65.4	17.9	16.7	2.0	1.13	5.6	SL
	6-12	0.3	58.6	23.2	18.2	0.8	1.49	5.5	SL
	10-16	2.2	57.3	22.9	19.8	1.4		5.7	SL
	16-20	50.7	82.3	8.3	9.3	–		6.3	GSL
	20+	72.4	87.4	4.0	8.7	–			VGLS
12	0-6	7.3	76.5	12.3	11.1	2.3	1.40	6.0	SL
	6-12	5.2	76.9	11.5	11.6	1.9	1.63	6.0	SL
	9-15	5.2	55.5	25.2	19.3	1.7		6.0	SL
	15-21	5.2	74.5	10.3	15.2	1.2		5.8	SL
	21-28	19.0	86.2	2.7	11.1	–		5.8	LS
	28-40	28.0	89.3	2.2	8.5	–		8.0	GLS
13	0-6	0.3	53.4	26.3	20.4	4.2	1.14	5.1	SCL
	6-12	0.5	46.2	30.3	23.4	1.6	1.55	5.0	L
	10-17	1.0	49.6	27.9	22.5	1.6		6.4	SCL
	17-25	16.8	85.3	4.1	10.6	–		6.7	LS
	25-31	12.0	88.4	1.5	10.0	–		7.4	LS
	31+	6.2	89.8	2.2	8.0	–		8.1	S
14	0-6	0.7	55.7	29.1	15.3	4.3	1.25	5.7	SL
	6-12	0.2	58.6	25.2	16.2	1.6	1.47	5.0	SL
	8-22	7.1	77.4	12.5	10.1	2.8		6.8	SL
	22-33	1.6	69.7	15.6	14.4	1.1		7.0	SL
	38-45	10.1	87.8	1.2	11.0	–		7.3	LS
	45+	30.4	86.1	3.9	10.0	–		7.7	GLS
15	0-6	1.0	57.6	24.6	17.8	2.9	1.36	5.5	SL
	6-12	2.9	55.2	25.4	19.4	1.2	1.56	5.4	SL
	8-16	1.9	57.9	23.8	18.3	0.9		6.1	SL
	16-24	6.2	87.7	3.2	9.1	–		6.3	LS
	24-34	27.8	79.6	10.8	9.6	–		7.9	GLS
16	0-6	1.5	46.5	34.1	19.5	3.0	1.28	5.6	L
	6-12	6.5	41.4	32.6	26.1	1.4	1.51	5.8	L
	12-20	24.5	75.3	13.6	11.1	0.8		7.0	GSL
	20-26	69.6	83.9	6.9	9.2	0.7		7.1	VGSL
	26-35	26.8	79.4	8.5	12.0	–		7.6	GSL
17	0-6	0.5	58.5	27.7	18.8	3.2	1.23	5.6	SL
	6-12	2.9	52.4	27.3	20.3	1.3	1.54	5.7	SCL
	13-19	20.2	86.9	3.5	9.5	0.8		6.0	GLS
	19-34	74.7	83.3	7.5	9.1	–			VGLS
	34-40	19.2	88.6	1.9	9.5	–		8.0	LS
18	0-6	2.8	78.8	8.0	13.1	1.1	1.69	5.9	SL
	6-12	3.8	81.7	5.2	13.1	1.0	1.84	5.8	SL
	10-18	8.2	87.9	1.5	10.6	0.3		6.3	LS
	18+	46.8	89.5	2.4	8.1	–		7.9	GS
19	0-6	0.6	56.5	24.1	19.3	3.2	1.34	5.3	SL
	6-12	2.4	56.6	25.2	18.2	1.2	1.57	5.2	SL
	12-20	2.0	45.5	30.5	23.0	0.7		5.8	L
	20-30	11.1	87.9	3.0	9.1	–		5.8	LS
	30-36	64.2	88.8	2.5	8.7	–		7.8	VGLS
20	0-6	0.5	58.7	23.5	17.8	2.7	1.21	6.0	SL
	6-12	2.0	57.7	24.1	18.3	1.3	1.44	5.8	SL
	11-14	3.5	72.2	10.5	17.3	0.2		6.7	SL
	14-19	4.2	84.0	2.8	13.2	0.2		6.7	LS
	19-29	19.8	88.4	2.5	9.1	–		6.5	LS
	29-40	48.5	89.4	2.1	8.5	–		8.0	GS

APPENDIX B. Summary of textural properties of Bonanza Valley soil profiles

Site no.	Profile depth (in.)	Gravel [1]	Sand [2]	Silt [2]	Clay [2]	O.M. [3]	B.D. [4]	pH	Textural class [5]
21	0-6	0.2	55.8	23.3	20.8	3.0	1.40	4.9	SCL
	6-12	0.1	49.9	27.2	22.8	1.4	1.39	4.9	SCL
	13-21	0.7	55.6	23.6	20.8	0.6		4.9	SCL
	21-29	10.6	86.4	3.6	10.1	0.3		6.4	LS
	29-40	22.0	90.7	0.3	9.0	–		6.2	GS
22	0-6	0.9	59.8	21.8	18.3	1.7	1.49	5.7	SL
	6-12	1.2	69.2	15.7	15.2	1.0	1.74	5.6	SL
	11-15	25.0	88.4	3.5	8.0	0.3		6.9	GLS
23	0-6	0.5	62.6	20.8	16.7	2.6	1.41	4.8	SL
	6-12	2.9	64.1	18.8	17.1	1.6		4.8	SL
	10-17	0.3	56.4	23.4	20.3	1.2		5.9	SCL
	17-23	2.4	84.4	4.0	11.6	0.2		6.6	LS
	23-40	33.2	89.1	1.8	9.0	–		7.8	GLS
24	0-6	0.4	55.1	25.5	19.4	3.5	1.33	4.6	SL
	6-12	0.8	52.2	25.4	22.4	1.6	1.41	4.8	SCL
	8-15	–	50.8	23.8	25.3	1.6		5.7	SCL
	15-20	0.7	43.6	32.8	23.5	0.7		5.8	L
	20-26	22.2	87.4	3.5	9.0	0.0		6.2	GLS
	26+	14.9	88.1	2.8	9.0	–		8.0	LS

APPENDIX C. Soil site descriptions

Site No. 1

Sampled as: Estherville loam[1]
Location: T126N-R36W-Sec. 23, NE_{160}, NE_{40}, NE_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE[2] (Colors are for moist soils)

- Ap 0-8″ Black (10YR 2/1) loam; weak very fine granular structure; friable; many roots; very strongly acid; abrupt smooth boundary.
- A1 8-18″ Black (10YR 2/1) coarse sandy loam; weak medium prismatic parting to weak very fine granular structure; friable; many roots; very strongly acid; gradual wavy boundary.
- B21 18-22″ Dark brown (10YR 4/3) loam; weak medium prismatic parting to very fine granular structure; friable; many roots; strongly acid; clear wavy boundary.
- B22 22-26″ Dark yellowish brown (10YR 3/4) loam; weak very fine granular structure; friable; many roots; strongly acid; abrupt wavy boundary.
- IIB3 26-42″ Dark brown (7.5YR 3/2) sand and gravel; single grained; loose; many roots; slightly acid; abrupt wavy boundary.
- IIC 42-60″ Yellowish brown (10YR 5/6) and strong brown (7.5YR 5/6) sand and gravel; single grained; loose; strong effervescence.

[1] This pedon is marginal to the Wadena series on the basis of laboratory data.
[2] Soil texture by mechanical analysis, soil organic matter content (O.M.), bulk density (B.D.), and soil acidity (pH) for each soil profile is listed in Appendix B.

Site No. 2

Sampled as: Estherville loam
Location: T126N-R36W-Sec 23, NW_{160}, NE_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

- Ap 0-7″ Black (10YR 2/1) loam; weak fine granular structure; friable; very strongly acid; gradual smooth boundary.
- A3 7-12″ Dark brown (7.5YR 3/2) loam; weak fine and medium subangular blocky structure; friable; clear wavy boundary.
- B2 12-15″ Dark brown (7.5YR 4/4) sandy loam; weak fine subangular blocky structure; friable; medium acid; clear wavy boundary.
- IIB3 15-21″ Dark brown (7.5YR 3/2) coarse gravelly sandy loam; single grained; friable; medium acid; clear wavy boundary.
- IIC1 21-60″ Brown (10YR 5/4) and strong brown (10YR 5/6) sand and gravel; single grained; friable; strong effervescence.

Site No. 3

Sampled as: Estherville loam[1]
Location: T125N-R36W-Sec. 4, NW_{160}, NE_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Plowed field
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-7″	Black (10YR 2/1) loam; weak fine subangular blocky parting to weak fine granular structure; friable; few roots; strongly acid; abrupt smooth boundary.
B2	7-13″	Dark brown (10YR 3/3) coarse sandy loam; weak fine subangular blocky parting to weak fine granular structure; friable; few roots; strongly acid; clear wavy boundary.
IIB3	13-18″	Dark brown (10YR 4/3) coarse sand; single grained; loose; medium acid; clear wavy boundary.
IIC1	18-27″	Dark brown (10YR 4/3) and dark gray (10YR 4/1) gravelly coarse sand; single grained; loose; slight effervescence; clear wavy boundary.
IIC2	27-60″	Yellowish brown (10YR 5/4), pale brown (10YR 6/3) and light yellowish brown (10YR 6/4) gravelly coarse sand; single grained; loose; slight effervescence.

[1] On the basis of laboratory data, this pedon is outside the range of the Estherville series because of the thinness of the loamy mantle. It is an undesignated series that is between the Estherville and Salida series.

Site No. 4

Sampled as:	Estherville loam
Location:	T125N-R36W-Sec. 4, NW_{160}, NE_{40}, NW_{10}
Field classification:	Typic Hapludoll
Vegetation:	Plowed field
Drainage:	Well
Setting:	1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-5″	Black (10YR 2/1) loam; weak fine granular structure; friable; many roots; very strongly acid; abrupt smooth boundary.
A3	5-10″	Very dark grayish brown (10YR 3/2) sandy loam; weak fine subangular blocky parting to weak fine granular structure; friable; many roots; strongly acid; clear wavy boundary.
B2	10-15″	Dark brown (10YR 3/4) sandy loam; weak fine subangular blocky structure; friable; medium acid; clear wavy boundary.
IIB3	15-23″	Dark yellowish brown (10YR 3/4) loamy coarse sand; single grained; loose; neutral; clear wavy boundary.
IIC1	23-32″	Dark brown (10YR 4/3) and dark yellowish brown (10YR 4/4) gravelly coarse sand; single grained; slight effervescence; loose; clear wavy boundary.
IIC2	32-60″	Brown (10YR 4/3), yellowish brown (10YR 5/6) and pale brown (10YR 6/3) coarse sand; single grained; slight effervescence; loose.

Site No. 5

Sampled as:	Estherville loam
Location:	T125N-R36W-Sec. 3, NW_{160}, SW_{40}, SW_{10}
Field classification:	Typic Hapludoll
Vegetation:	Oats
Drainage:	Well
Setting:	1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-8″	Black (10YR 2/1) loam; weak fine granular structure; friable; many roots; very strongly acid; abrupt smooth boundary.
B21	8-16″	Dark brown (10YR 3/3) grading to dark brown (7.5 YR 4/4) with depth sandy loam; weak fine and medium subangular blocky structure; friable; few roots; strongly acid; clear smooth boundary.
B22	16-21″	Dark brown (7.5YR 4/4) loamy coarse sand; single grained; loose; few roots; slightly acid; abrupt smooth boundary.
IIB3	21-24″	Very dark grayish brown (10YR 3/2) gravelly coarse sand; single grained; loose; few roots; neutral; abrupt smoth boundary.
IIC1	24-28″	Dark brown (7.5YR 4/4) and brown (7.5YR 5/4) gravelly coarse sand; single grained; loose; few roots; neutral; abrupt smooth boundary.
IIC2	28-60″	Pale brown (10YR 6/3), light yellowish brown (10YR 6/4), and yellowish brown (10YR 5/4) coarse sand; about 5% gravel; single grained; loose; slight effervescence.

Site No. 6

Sampled as:	Estherville[1]
Location:	T125N-R36W-Sec. 3, NW_{160}, SW_{40}, NW_{10}
Field classification:	Typic Hapludoll
Vegetation:	Oats
Drainage:	Well
Setting:	1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-6″	Black (10YR 2/1) loam; weak fine granular structure; friable; few roots; very strongly acid; abrupt smooth boundary.
B21	6-13″	Dark yellowish brown (10YR 3/4) loam; weak medium and coarse subangular blocky structure; friable; few roots; strongly acid; gradual wavy boundary.

B2 13-17″ Strong brown (7.5YR 3/4) coarse sand; single grained; loose; medium acid; clear wavy boundary.

IIB3 17-26″ Dark yellowish brown (10YR 4/4) sand; single grained; loose; slightly acid; abrupt wavy boundary.

IIC1 26-38″ Light yellowish brown (10YR 6/4), brown (10YR 5/3), and yellowish brown (10YR 5/4) fine sand and medium sand; single grained; loose; slight effervescence; abrupt wavy boundary.

IIC2 38-60″ Pale brown (10YR 6/3), light yellowish brown (10YR 6/4), and yellowish brown (10YR 5/2) coarse sand; single grained; loose; slight effervescence.

[1] On the basis of laboratory data, this pedon is outside the range of the Estherville series because of the thinness of the loamy mantle. It is an undesignated series that is between the Estherville and Salida series.

Site No. 7

Sampled as: Estherville loam (thick solum phase)
Location: T125N-R37W-Sec. 12, NW_{160}, SW_{40}, SW_{10}
Field classification: Typic Hapludoll
Vegetation: Diverted acres—weedy
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-6″ Black (10YR 2/1) loam; weak fine granular structure; friable; few roots; slightly acid; abrupt smooth boundary.

A3 6-11″ Dark grayish brown (10YR 3/2) loam; weak very fine granular structure; friable; few roots; medium acid; gradual smooth boundary.

B21 11-19″ Strong brown (7.5YR 3/3) loam; weak medium and coarse subangular blocky structure; friable; few roots; medium acid; clear wavy boundary.

B22 19-24″ Strong brown (7.5YR 3/4) loam; weak medium subangular blocky structure; friable; many roots; medium acid; clear wavy boundary.

IIB3 24-32″ Dark brown (7.5YR 3/2) and strong brown (7.5YR 3/4) gravelly loamy coarse sand; single grained; loose; slightly acid; clear wavy boundary.

IIC 32-60″ Grayish brown (10YR 5/2), pale brown pale brown (10YR 6/3), and light yellowish brown (10YR 6/4) gravelly coarse sand; single grained; loose; slight effervescence.

Site No. 8

Sampled as: Estherville loam[1]
Location: T125N-R37W-Sec. 12, NW_{160}, SW_{40}, SW_{10}
Field classification: Typic Hapludoll
Vegetation: Diverted acres—weedy
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-6″ Black (10YR 2/1) loam; weak fine granular structure; friable; few roots; strongly acid; abrupt smooth boundary.

A3 6-10″ Dark grayish brown (10YR 3/2) loam; weak medium subangular blocky grading to weak fine granular structure; friable; few roots; strongly acid; clear smooth boundary.

B2 10-17″ Dark yellowish brown (10YR 4/3) loam; weak medium subangular blocky grading to coarse subangular blocky structure; friable; few roots; medium acid; abrupt wavy boundary.

IIB3 17-21″ Dark brown (7.5YR 3/2) and dark grayish brown (10YR 3/2) coarse sand and gravel; single grained; loose; few roots; mildly alkaline; abrupt wavy boundary.

IIC1 21-60″ Strong brown (7.5YR 3/2), yellowish red (5YR 4/6), and pale brown (10YR 6/3) coarse sand and gravel; single grained; loose; slight effervescence.

[1] On the basis of laboratory data, this pedon is within the Kanaranzi series. It contains more clay in the loamy mantle than is allowed in the Estherville series.

Site No. 9

Sampled as: Estherville loam
Location T124N-R36W-Sec. 21, SE_{160}, NE_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-7″ Black (10YR 2/1) loam; weak very fine granular structure; very friable; few roots; very strongly acid; abrupt smooth boundary.

B2 7-15″ Dark brown (7.5YR 3/2) loam; weak medium subangular blocky structure; friable; few roots; strongly acid; abrupt wavy boundary.

IIB3 15-23″ Dark brown (7.5YR 3/2) gravelly loamy coarse sand; single grained; about 5% gravel; loose; abrupt wavy boundary.

IIC1 23-60″ Pale brown (10YR 6/3), grayish brown (10YR 5/2), and brown (10YR 5/3) coarse sand; single grained; loose; slight effervescence.

Site No. 10

Sampled as: Estherville loam[1]
Location T124N-R36W-Sec. 21, SE_{160}, NE_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-7″ Black (10YR 2/1) loam; weak granular structure; friable; many roots; strongly acid; abrupt smooth boundary.

B21 7-12″ Dark grayish brown (10YR 3/2) and dark brown (10YR 3/3) loam; moderate fine subangular blocky structure; friable; many roots; strongly acid; clear smooth boundary.

B22 12-18″ Dark yellowish brown (10YR 3/4) loam); moderate fine subangular blocky structure; friable; many roots; slightly acid; clear wavy boundary.

IIB3 18-36″ Dark brown (7.5YR 3/2) coarse sand; single grained; loose; strongly acid; clear wavy boundary.

IIC1 26-60″ Brown (10YR 5/3), yellowish brown (10YR 5/4), and yellowish brown (10YR 5/5) gravelly coarse sand; single grained; about 20% gravel; loose; strong effervescence.

[1] On the basis of laboratory data, this pedon is within the Kanaranzi series. It contains more clay in the loamy mantle than is allowed in the Estherville series.

Site No. 11

Sampled as: Estherville sandy loam
Location T123N-R35W-Sec. 22, NE_{160}, NE_{40}, NW_{10}
Field classification: Typic Hapludolls; coarse-loamy over sandy or sandy skeletal, mixed, mesic.
Vegetation: Alfalfa and grass sod mixed
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-6″ Black (10YR 2/1) sandy loam; weak medium granular structure; friable; medium acid; abrupt smooth boundary.

A3 6-10″ Very dark brown (10YR 2/2) sandy loam; weak medium subangular blocky structure; friable; strongly acid; clear wavy boundary.

B2 10-16″ Dark brown (7.5YR 4/4) sandy loam; weak fine and medium subangular blocky structure; friable; medium acid; gradual wavy boundary.

IIB3 16-20″ Dark brown (7.5YR 3/2) gravelly loamy coarse and medium sand; single grained; loose; slightly acid; clear irregular boundary.

IIC1 20-32″ Yellowish brown (10YR 5/8) gravelly coarse sand; single grained; loose; lime skirts on gravel particles; 50% gravel up to 3″ diameter; strong effervescence, mildly alkaline, clear wavy boundary.

IIC2 32+ Pale brown (10YR 6/3) and light yellowish brown (10YR 6/4) gravelly coarse sand; single grained; loose; 10-20% gravel; strong effervescence; moderately alkaline.

Site No. 12

Sampled as: Estherville coarse sandy loam
Location T123N-R35W-Sec. 22, NE_{160}, NE_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa and grass sod
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-9″ Very dark brown (10YR 2/2) coarse sandy loam; weak very fine subangular blocky structure; friable; medium acid; abrupt smooth boundary.

A3 9-15″ Dark brown (10YR 3/3) coarse sandy loam; weak very fine subangular blocky structure; friable; medium acid; gradual wavy boundary.

B2 15-21″ Dark yellowish brown (10YR 4/4) coarse sandy loam; weak fine subangular blocky structures; very friable; medium acid; gradual wavy boundary.

IIB3 21-28″ Yellowish brown (10YR 5/6) gravelly loamy coarse sand; single grained; loose; medium acid; abrupt wavy boundary.

IIC 28-40″ Light yellowish brown (10YR 6/4) coarse sand and gravel; single grained; loose; strong effervescence; moderately alkaline.

Site No. 13

Sampled as: Estherville coarse sandy loam[1]
Location T123N-R35W-Sec. 9, SW_{160}, NW_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Corn
Drainage: Well
Setting: 2 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-10″ Very dark brown (10YR 2/2) coarse sandy loam; weak fine and very fine subangular blocky structure; friable; strongly acid;abrupt smooth boundary.

B2 10-17″ Dark yellowish brown (10YR 3/4) coarse sandy loam; moderate fine subangular blocky structure; friable; strongly acid; clear wavy boundary.

IIB3 17-25" Dark yellowish brown (10YR 4/4) gravelly coarse sand; single grained; loose; neutral; abrupt wavy boundary.

IIC1 25-31" Brown (10YR 4/3) gravelly coarse sand; single grained; loose; strong effervescence; mildly alkaline; gradual wavy boundary.

IIC2 31-40" Pale brown (10YR 6/3) coarse sand; single grained; loose; strong effervescence; moderately alkaline.

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[1] On the basis of laboratory data, this pedon is within the Kanaranzi series. It contains more clay in the loamy mantle than is allowed in the Estherville series.

Site No. 14

Sampled as: Unnamed
Location: T123N-R35W-Sec. 9, SW_{160}, NW_{40}, NW_{10}
Field classification: Cumulic Hapludolls
Vegetation: Corn
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-8" Black (10YR 2/1) sandy loam; weak fine subangular blocky structure; very friable; medium acid; abrupt smooth boundary.

A1 8-22" Black (10YR 2/1) sandy loam; weak fine subangular blocky structure; very friable; neutral; clear wavy boundary.

A3 22-23" Very dark brown (10YR 2/2) sandy loam; weak medium subangular blocky structure; very friable; neutral; clear wavy boundary.

B2 33-45" Dark yellowish brown (10YR 4/4) loamy sand; weak coarse subangular blocky structure parting to single grained; very friable; neutral; clear wavy boundary.

C 45"+ Yellowish brown (10YR 5/4) gravelly coarse sand; single grained; loose; mildly alkaline.

Site No. 15

Sampled as: Estherville loam
Location: T123N-R35W-Sec. 22, NE_{160}, SW_{40}, SE_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-5" Black (10YR 2/1) loam; weak fine subangular blocky structure; very friable; strongly acid; abrupt smooth boundary.

A3 5-8" Very dark brown (10YR 2/2) loam; weak medium subangular blocky structure; friable; strongly acid; clear wavy boundary.

B2 8-16" Very dark grayish brown (10YR 3/2) loam; weak medium subangular blocky structure; friable; slightly acid; clear wavy boundary.

IIB3 16-24" Dark brown (10YR 4/3) loamy coarse sand; single grained; loose; slightly acid; clear wavy boundary.

IIC1 24-34" Brown (10YR 5/3) and yellowish brown (10YR 5/4) gravelly coarse sand; single grained; loose; moderately alkaline; clear wavy boundary.

IIC2 34+" Yellowish brown (10YR 5/4) coarse sand; many fine faint yellowish brown (10YR 5/8) mottles; single grained; loose; violent effervescence.

Site No. 16

Sampled as: Unnamed[1]
Location: T123N-R35W-Sec. 22, NE_{160}, SW_{40}, SW_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap 0-7" Very dark brown (10YR 2/2) very fine sandy loam; weak fine and very fine subangular blocky structure; friable; medium acid; abrupt smooth boundary.

B2 7-12" Dark brown (10YR 3/3) very fine sandy loam; weak fine and very fine subangular blocky structure; friable; medium acid; abrupt wavy boundary.

IIB3 12-20" Very dark grayish brown (10YR 3/2) gravelly loamy coarse sand; single grained; loose slight effervescence; neutral; abrupt wavy boundary.

IIC1 20-26" Yellowish brown (10YR 5/6) coarse sand and gravel; single grained; loose; 20 to 35% coarse fragments larger than 3" diameter; strong effervescence; neutral; abrupt wavy boundary.

IIC2 26-35" Dark yellowish brown (10YR 4/4) coarse sand and gravel; single grained; loose; strong effervescence; mildly alkaline; gradual wavy boundary.

IIC3 35-40" Yellowish brown (10YR 5/4) coarse sand; single grained; loose; strong effervescence.

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[1] On the basis of the laboratory analysis, this pedon is within the Estherville series.

Site No. 17

Sampled as: Estherville coarse sandy loam[1]
Location: T123N-R35W-Sec. 9, SW_{160}, SW_{40}, NW_{10}
Field classification: Typic Hapludoll
Vegetation: Corn
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-9″	Very dark brown (10YR 2/2) coarse sandy loam; moderate fine and very fine subangular blocky structure; friable; medium acid; abrupt wavy boundary.
B2	9-13″	Dark brown (10YR 3/3) coarse sandy loam; weak very fine subangular blocky structure; friable; medium acid; clear wavy boundary.
IIB3	13-19″	Dark yellowish brown (10YR 3/4) gravelly coarse sand; single grained; loose; medium acid; clear wavy boundary.
IIC1	19-34″	Dark yellowish brown (10YR 3/4) loose; 20-35% coarse fragments larger than 3″ diameter; strong effervescence; clear wavy boundary.
IIC2	34-40″	Pale brown (10YR 6/3) coarse sand; single grained; loose; strong effervescence; moderately alkaline.

[1] On the basis of laboratory data, this pedon is outside of the Estherville series because of the thinness of the loamy mantle. It is an undesignated series between Estherville and Salida series.

Site No. 18

Sampled as: Unnamed[1]
Location: T123N-R35W-Sec. 9, SW_{160}, SW_{40}, NW_{10}
Field classification: Entic Hapludolls
Vegetation: Corn
Drainage: Excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-10″	Very dark brown (10YR 2/2) loamy sand; weak fine subangular blocky structure; very friable; medium acid; abrupt wavy boundary.
B2	10-18″	Dark yellowish brown (10YR 4/4) sand; weak coarse subangular blocky structure parting to single grained; loose; slightly acid; clear wavy boundary.
C	18+″	Light yellowish brown (10YR 6/4) gravelly coarse sand; single grained; line of 2 mm to 2″ gravel at 28″, reddish brown (5YR 4/3); moderately alkaline.

[1] On the basis of laboratory data, this pedon is outside of the Estherville series because of the thinness of the loamy mantle. It is an undesignated series between Estherville and Salida series.

Site No. 19

Sampled as: Estherville loam[1]
Location: T123N-R34W-Sec. 22, SW_{160}, NE_{40}, NE_{10}
Field classification: Typic Hapludoll
Vegetation: Corn
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-8″	Black (10YR 2/1) loam; weak medium subangular blocky structure; friable; strongly acid; abrupt smooth boundary.
A3	8-12″	Very dark grayish brown (10YR 3/2) loam; weak medium subangular blocky structure; friable; strongly acid; clear wavy boundary.
B2	12-20″	Dark yellowish brown (10YR 4/4) loam; weak coarse subangular blocky structure; friable; medium acid; clear wavy boundary.
B3	20-30″	Yellowish brown (10YR 5/4) loamy coarse sand; single grained; loose; strong effervescence; mildly alkaline.

[1] On the basis of laboratory analysis, this pedon is within the range of the Kanaranzi series, but it is marginal to the Estherville series.

Site No. 20

Sampled as: Estherville coarse, sandy loam
Location: T123N-R34W-Sec. 22, SW_{160}, NE_{40}, NE_{10}
Field classification: Typic Hapludoll
Vegetation: Corn
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-11″	Very dark brown (10YR 2/2) coarse sandy loam; weak fine subangular blocky structure; friable; medium acid; abrupt smooth boundary.
B21	11-14″	Dark brown (7.5YR 4/4) coarse sandy loam; weak fine subangular blocky structure; friable; neutral abrupt wavy boundary.
IIB22	14-19″	Dark brown (7.5YR 4/4) loamy coarse sand; weak very fine subangular blocky structure; very friable; neutral; clear wavy boundary.
IIB3	19-29″	Strong brown (7.5YR 5/6) medium and coarse sand; single grained; loose; slightly acid; clear irregular boundary.
IIC	29-40″	Yellowish brown (10YR 5/4) coarse sand and gravel; single grained; loose; strong effervescence; moderately alkaline.

Site No. 21

Sampled as: Estherville loam[1]
Location: T124N-R36W-Sec. 27, SE_{160}, SW_{40}, SE_{10}
Field classification: Typic Hapludoll
Vegetation: Alfalfa
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-8″	Black (10YR 2/1) loam; weak fine granular structure; friable; very strongly acid; abrupt smooth boundary.
A3	8-13″	Very dark grayish brown (10YR 3/2) loam; weak fine granular structure; friable; very strongly acid; clear wavy boundary.
B21	13-21″	Dark yellowish brown (10YR 4/4) loam; weak fine subangular blocky structure; friable; very strongly acid; clear wavy boundary.
IIB22	21-29″	Dark brown (10YR 4/3) loamy sand; single grained; friable; slightly acid; clear wavy boundary.
IIB3	29-40″	Dark brown (7.5YR 4/4) coarse sand and fine gravel; single grained; friable; slightly acid; gradual wavy boundary.
IIC	40-60″	Yellowish brown (10YR 5/4) and brown (10YR 5/3) coarse sand and fine gravel; single grained; loose; slight effervescene.

[1] On the basis of laboratory analysis, this pedon is within the range of the Kanaranzi series, but it is marginal to the Estherville series.

Site No. 22

Sampled as: Estherville loam[1]
Location: T124N-R36W-Sec. 27, SE_{160}, SW_{40}, SE_{10}
Field classification: Typic Hapludoll
Vegetation: Corn
Drainage: Well
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-6″	Black (10YR 2/1) loam; weak fine granular structure; friable; medium acid; abrupt smooth boundary.
B21	6-11″	Dark brown (10YR 3/3) sandy clay loam; moderate subangular blocky structure; friable; medium acid; abrupt smooth boundary.
IIB22	11-15″	Dark brown (7.5YR 3/2) coarse sand; single grain; friable; neutral; abrupt wavy boundary.
IIB3	15-24″	Pale brown (10YR 6/3) and light yellowish brown (10YR 6/4) medium sand; single grained; loose; neutral; abrupt wavy boundary.
IIC	24-60″	Grayish brown (10YR 5/2), brown 10YR 5/3), and pale brown (10YR 6/3) coarse sand and gravel; single grained; loose; slight effervescence.

[1] On the basis of laboratory data, this pedon is outside of the Estherville series because of the thinness of the loamy mantle. It is an undesignated series between Estherville and Salida series.

Site No. 23

Sampled as: Estherville coarse sandy loam
Location: T123N-R35W-Sec. 6, SE_{160}, NE_{40}, NE_{10}
Field classification: Typic Hapludoll
Vegetation: Soybeans
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-10″	Very dark brown (10YR 2/2) coarse sandy loam; weak very fine subangular blocky structure; friable; very strongly acid; abrupt smooth boundary.
B2	10-17″	Dark yellowish brown (10YR 3/4) coarse sandy loam; weak fine subangular blocky structure parting to weak very fine subangular blocky structure; friable; medium acid; gradual wavy boundary.
IIB3	17-23″	Dark yellowish brown (10YR 4/4) medium and coarse sand; single grained; loose; neutral; abrupt wavy boundary.
IIC	23-40″	Pale brown (10YR 6/3) stratified coarse sand and gravel; single grained; loose; strong effervescence; mildly alkaline.

Site No. 24

Sampled as: Estherville loam[1]
Location: T123N-R35W-Sec. 6, SE_{160}, NW_{40}, NE_{10}
Field classification: Typic Hapludoll
Vegetation: Soybeans
Drainage: Somewhat excessive
Setting: 1 percent slope

SOIL PROFILE (Colors are for moist soils)

Ap	0-8″	Black (10YR 2/1) loam; weak medium subangular blocky structure; friable; very strongly acid; abrupt smooth boundary.
A3	8-15″	Very dark brown (10YR 2/2) loam; weak medium subangular blocky structure; friable; medium acid; clear wavy boundary.
B2	15-20″	Dark brown (10YR 4/3) loam; weak medium subangular blocky structure; friable; medium acid; clear wavy boundary.
IIB3	20-26″	Dark reddish brown (5YR 3/4) loamy coarse sand; weak coarse subangular blocky parting to single grain; very friable; 15% coarse fragments; slightly acid; clear wavy boundary.
IIC	26+″	Pale brown (10YR 6/3) coarse sand; single grained; loose; 10% coarse fragments; moderately alkaline.

[1] On the basis of laboratory data, this pedon is within the Kanaranzi series. It contains more clay in the loamy mantle than is allowed in the Estherville series.

Here is a profile view of a typical droughty soil in the Bonanza Valley. The soils are characteristically shallow, underlain with sands and/or gravels. This publication reports a study of the physical properties of drought-hazard soils (principally the Estherville series) in the Bonanza Valley area of central Minnesota.

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