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DEVELOPING OPTIMUM DRAINAGE DESIGN GUIDELINES FOR THE RED RIVER BASIN

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1 Introduction

Artificial subsurface drainage has produced some of the most productive soils in the world and continues to be a common water management practice in Minnesota, the upper Midwest, and throughout the world. The agronomic and environmental benefits of subsurface agricultural drainage are many, including improved crop growth and yield, improved soil trafficability and field operations, and a decrease in sediment and phosphorus losses from poorly drained agricultural fields. A significant percentage of agricultural soils in the Red River Basin (RRB) may potentially benefit from subsurface drainage because of persistent high water tables, particularly during springtime, and a relatively short growing season. Installation of new subsurface drainage systems continues to increase in the RRB.

In Minnesota and elsewhere in the region, the design approach for new drainage systems has changed little since the mid-1900's. For example, the Minnesota Drainage Guide lists drain spacings for Minnesota soils, for four drainage coefficients (0.25, 0.375, 0.5, 0.75 inches/day) and two drainage depths (3 and 4 ft), but provides no guidance to drainage practitioners on how these drainage depth x spacing combinations influence profitability and hydrology.

We have recently calibrated (tested) the drainage simulation model, DRAINMOD, using data from the Southern Research and Outreach Center – Waseca drainage project[1]. The results obtained show a close agreement between the observed and the simulated values of both drainage volume and crop yield. Based on these results, we are currently conducting a research project, supported by the Minnesota Corn Research and Promotion Council, to investigate optimum drainage design guidelines for major soils in the Minnesota River Basin. Sands and Canelon[2] recently conducted uncalibrated DRAINMOD simulations using estimated properties for three soils in the RRB.

The goal of this work was to develop a more sophisticated hydrologic model for important soils in the RRB using measured soil parameters, by pursuing the following three objectives:
(1) conducting sampling and analysis for up to six soils in the RRB; (2) performing DRAINMOD

[1] Luo, W., G.R. Sands, M. Youssef, J.S. Strock , I. Song, and D. Canelon. 2010. Modeling the impact of alternative drainage practices in the northern cornbelt with DRAINMOD-NII. Agricultural Water Management 297(2010):389-398.

[2] Sands, G.R. and D. Canelon (2010). Long-term field-scale computer simulation of subsurface drainage for three soils common to Northwest Minnesota. Unpublished Report to the Red River Watershed Management Board - Technical Advisory Committee.

computer simulations for these soils for three locations, three drainage depths, and several drainage intensities (drain spacings); (3) disseminating the project results and conclusions through Extension channels.

2 Methods and Procedures

2.1 Computer Modeling Framework - DRAINMOD

The first computer simulation models for subsurface drainage were based on a water balance equation in the soil profile, in contrast to models based on a solution to Richard's equation (Skaggs, 1999)[3]. Numerous drainage models have been developed over the years, employing various approaches to solve drainage problems. Of the water balance models, DRAINMOD (Skaggs, 1976[4]) has become one of the most widely used subsurface drainage models throughout the world (Skaggs, 1999). The model was developed for a shallow water table soil. It has been used as a tool for optimizing the design of surface and subsurface drainage systems and includes a routine for considering surface or subsurface irrigation. The model is well documented by Skaggs (1978, 1980a, 1980b)[5]. Many reports of validation studies for the model that used field data from different regions of U.S. have been reported and, over the years, DRAINMOD was further developed to include soil nitrogen and salinity budgeting, and more recently, frozen soil and snowmelt hydrology.

DRAINMOD core hydrology component is based on computing a water balance at the midpoint between parallel drains, employing Kirkham's (1957)[6] and Hooghoudt's (Bouwer and Van Shilfgaard, 1963)[7] equations for predicting drainage rate, depending on the location of the water table relative to the drain.

DRAINMOD incorporates components for snow accumulation/melting and frozen soil dynamics. The model assumes that precipitation occurs as snow when the average daily temperature is below a user-input rain/snow dividing base temperature. Snow depth is accumulated to

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[3] Skaggs, R.W. 1999. Drainage simulation models. In Agricultural Drainage, 31. R. W. Skaggs and J. Van Schilfgaarde, eds. Agronomy No. 38. Madison, Wisc.: ASA-CSSA-SSSA.

[4] Skaggs, R.W. 1976. Determination of the hydraulic conductivity – Drainable porosity ratio from water table measurements. Trans. ASAE 19(1): 73-80, 84.

[5] Skaggs, R.W. 1978. A water management model for shallow water table soils. Technical Report No. 134. Raleigh, N.C.: North Carolina State University, Water Resources Institute of the University of North Carolina.

Skaggs, R.W. 1980a. A water management model for artificial drained soils. Technical Bulletin No. 276. Raleigh, N.C.: North Carolina State University, North Carolina Agricultural Research Service.

Skaggs, R.W. 1980b. DRAINMOD-reference report: Methods for design and evaluation of drainage-water management systems for soil with high water tables. Fort Worth, Texas: USDA-SCS, South National Technical Center.

[6] Kirkham, D. 1957. Theory of land drainage. In Drainage of Agricultural Lands, 139-181. J. N. Luthin, ed. Agronomy No. 7. Madison, Wisc.: ASA-CSSA-SSSA.

[7] Bouwer, H., and J. Van Schilfgaarde. 1963. Simplified method of predicting fall of water table in drained land. Trans. ASAE 6(4): 288-291.

ultimately become snowmelt when air temperature rises above a snowmelt base temperature (0°C for our simulations). DRAINMOD simulates frozen soils by simultaneously solving the water flow equation and heat flow equation based on the principles of mass and energy conservation. When freezing conditions are indicated by below-zero temperatures, the model calculates ice content in the soil profile and modifies soil hydraulic conductivity and infiltration rate accordingly.

DRAINMOD does not model crop growth but rather, simulates crop stress and yield reduction from potential yield due to 1) excess water stress, 2) drought stress, 3) yield reduction due to planting delay, and 4) salinity stress (not incorporated in the present work).

2.2 Modeling Locations

Drainage simulations were conducted at three locations in the RRB: Fergus Falls, Crookston, and Roseau. These locations were selected based on two criteria: availability of climate data, distribution from north to south in the RRB. The three locations are presented in Table 1. Fergus Falls receives 16 percent more annual precipitation and more annual snowfall than both Crookston and Roseau.

Table 1. Three simulation locations and representative climate characteristics.

Location	Annual Precip (in)	Annual Snowfall (in)	Mean Annual Temp (^{o}F)
Fergus Falls	24	47	42
Crookston	21	42	40
Roseau	21	36	37

2.3 Precipitation, Temperature, and Evapotranspiration Input Data

DRAINMOD requires hourly precipitation and daily maximum/minimum temperatures. Daily precipitation and temperature data were obtained from the National Weather Service in the locations of interest for the period 1913 to 2011. Hourly precipitation was then derived from observed daily records, using the CLIGEN model (Nicks and Lane, 1989)[8] and a procedure similar to that of Elliot et al. (1992)[9]. Storm durations for the observed daily precipitation depths were simulated with CLIGEN using the statistical parameters for the RRB that come packaged with the model. The simulated storm durations and the Soil Conservation Service (SCS) Type II curve

[8] Nicks, A.D. and L.J. Lane. 1989. Weather generator, Chap. 2 in USDA-Water Erosion Prediction Project: Hillslope Profile Model Documentation. NSERL Report No. 2, Eds. L.J. Lane, and M.A. Nearing, 2.1-2.18. West Lafayette, IN: USDA-ARS National Soil Erosion Research Laboratory.

[9] Elliot, W. J., W. Qiong, and A. V. Elliot. 1992. Suitability of CLIGEN for generating rainfall data for DRAINMOD. Applied Engineering in Agriculture 8(6): 807-812.

rainfall distribution (SCS, 1973)[10] were used to distribute the daily precipitation amounts to an hourly basis. Examples of distributing precipitation using the SCS Type II curve can be found in Haan et al. (1994)[11]. Elliot et al. (1992) reported that drainage depths simulated with DRAINMOD using a similar procedure consisting of a triangular intensity distribution compared extremely well to simulations using observed hourly precipitation.

Potential evapotranspiration (ET) can either be computed directly in DRAINMOD using the Thornthwaite method, or computed by any other method of the user's choice and input to the model as a file. We chose to use the Thornthwaite method for computing ET for the simulation record for each location, and DRAINMOD estimates actual ET based on soil moisture availability and stage of crop/root development. The simulation record chosen was 99 years because that is the maximum period allowed by the CLIGEN model.

The DRAINMOD algorithms for soil freeze/thaw and snow accumulation/melting were implemented for this work. When freezing conditions are indicated by below zero temperatures, the model calculates ice content in the soil profile and modifies soil hydraulic conductivity and infiltration rate accordingly. When precipitation occurs on days where the high temperature is below the threshold for snowfall, precipitation is assumed to be in the form of snow and is accumulated on the soil surface. When milder temperatures occur, snow that has accumulated can melt and become available for infiltration and surface runoff.

2.4 Soils

2.4.1 Soil Selection

The NRCS national soil database and ArcGIS software was implemented to find the most commonly occurring soils in the poorly drained drainage classes and hydrologic soil groups. Figure 1 displays the area of interest in the Red River Basin and the distribution of poorly drained soils by "hydrologic group" and "drainage class". Table 2 displays the six soils chosen for the simulation study and their estimated area extent in the RRB.

2.4.2 Soil Input Data

DRAINMOD requires detailed input data for each soil layer, such as water retention and saturated hydraulic conductivity (Ks). Input soils data were derived in two ways, because of data availability: Input data for three of selected soils (Bearden, Fargo and Hegne) were taken from measured values contained in the Soil Survey of the Northwest Experiment Station (Rust and Erickson, 1975) [12] at Crookston, MN. Soils data taken from the survey included water content at field capacity and permanent wilting point, bulk density, and percentages of sand, silt and clay. Data for the other three soils (Borup, Colvin and Ulen) were derived from samples

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[10] Soil Conservation Service. 1973. A method for estimating volume and rate of runoff in small watersheds. SCS-TP-149. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, D.C.

[11] Haan, C. T., B. J. Barfield, and J. C. Hayes. 1994. Design hydrology and sedimentology for small catchments. Academic Press Limited, London. pp 46-47.

[12] Rust, R. H. and R. A. Erickson. 1975. Soil Survey of the Northwest Experiment Station. Agricultural Experiment Station, University of Minnesota, Department of Soil Science, Soil Series No. 100-1975.

taken at the Northwest Experiment Station and sent to a commercial lab for analysis. Agvise laboratories provided measured values of water retention for seven values of capillary pressure (39, 131, 394, 1181, 2362, 3937 and 5905 inches of head).

Soil parameters obtained from the survey and laboratory were then used as inputs for the Rosetta model (Schaap, 2000) [13] , which was used to generate parameters for the van Genuchten equation (van Genuchten, 1980)[14]. Finally, the complete water retention curve for each soil was generated using the van Genuchten equation as follows:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|\psi|)^n\right]^{1-1/n}}$$

Where, $\theta(\psi)$ is the soil water content at pressure, ψ; θ_s is the saturated water content (porosity); θ_r is the residual water content; α is a coefficient related to the air entry pressure of the soil ($\alpha > 0$), and n is a measure of the pore-size distribution ($n > 1$). The values for α, n, θ_s and θ_r were obtained from the Rosetta model for each soil.

For all soils, values of saturated hydraulic conductivity were taken from the Minnesota Drainage Guide[15], based on the premise that the Guide is widely used drainage practitioners and thus, drain spacings used for the study would correspond with what is being used in the field. Table 3 displays the physical data for all six soils, used for model inputs. Figure A1 in the Appendix, displays the soil moisture retention curves for the six soils.

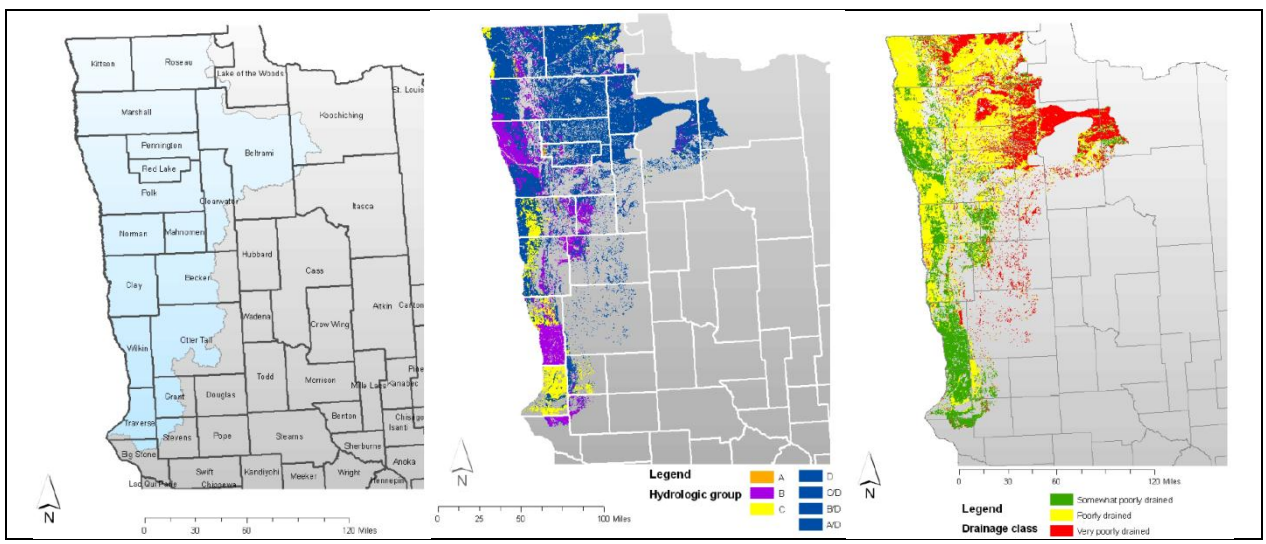

Figure 1. Counties of the Minnesota Red River Basin included in the soil selection process.

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[13] Schaap, M. G. 2000. ROSETTA model. United Sates Salinity Laboratory (USSL). ARS-USDA. http://www.ussl.ars.usda.gov/MODELS/rosetta/rosetta.htm.

[14] Van Genuchten, M. Th. 1980. A closed-form equation for predicting saturated the conductivity of unsaturated soils. Soil Science Society of America Journal, 44(5):892-898.

[15] United States Department of Agriculture-Soil Conservation Service. 1984. Minnesota Drainage Guide. USDA-SCS, St. Paul, MN.

Table 2. Soils chosen for the simulation study and their drainage class.

Soil	Drainage Class[§]	Hydro Soil Group	RRB Extent (1000 acres)
Bearden	SPD	C	468
Borup	VPD	B/D	466
Colvin	PD	B/D, C/D	240
Fargo	PD	D	224
Hegne	PD	C/D, D	58
Ulen	SPD	A, B	113

[§] SPD=*somewhat poorly drained*; PD=*poorly drained*; VPD=*very poorly drained*

2.5 Crop Input Data

Continuous corn was used for all simulations with a cropping window from Apr 25 to Sep 20, with optimum planting dates of May 1-7. These values were based on input from Extension corn specialists at the University of Minnesota. DRAINMOD simulates planting date and harvest date within specified planting and harvesting windows, subject to trafficable soil conditions, as estimated from continuous simulation of soil moisture relationships and pore air volume.

2.6 Drainage Design

The combination of drainage depth and spacing determines the drainage "intensity" for a given soil and affects the hydraulic and hydrologic response of the drainage system. Three drainage depths (3.0, 3.5, and 4.0 feet) and four drain spacings, in addition to an undrained condition, were simulated for each soil-location combination. This resulted in a total of 234 individual model simulations (78 at each location).

Table 4 displays the four drain spacings chosen for each soil, based on the drain spacing estimates found in Minnesota Drainage Guide. These drain spacings, combined with the three drainage depths, were selected such that the daily drainage rates for all combinations for a given soil would be bracketed by the 0.125 and 0.5 inches/day drainage rates: the 4 ft x narrowest spacing resulted in 0.5 inches/day drainage rate and the 3 ft x widest spacing resulted in the 0.125 inches/day drainage rate. Table 5 illustrates this concept.

Table 3. Physical data for six soils used in the study.

	Depth (in)	Sand (%)	Silt (%)	Clay (%)	BD (g/cm^3)	Por (%)	FC (%)	PWP (%)	Ks (in/h)
Bearden	0-7	47.0	25.3	27.9	1.15	56.6	29.1	13.9	0.40
	7-10	52.3	23.2	24.6	1.29	51.3	24.0	9.8	1.10
	10-19	11.1	44.2	44.9	1.30	50.9	31.7	11.9	1.10
	19-30	7.9	52.2	40.0	1.35	49.1	28.4	11.5	1.09
	37-49	10.3	52.2	37.7	1.35	49.1	26.9	10.4	1.03
	49-64	5.7	21.4	73.0	1.45	45.3	37.0	17.6	1.03
Borup	0-6	42.0	27.0	31.0	1.47	44.5	35.6	26.5	4.00
	6-18	51.3	33.7	15.0	1.55	41.5	26.4	11.4	4.00
	18-30	28.0	59.0	13.0	1.45	45.4	24.5	10.7	9.84
	30-42	36.0	47.0	17.0	1.43	45.9	33.0	14.4	11.00
Colvin	0-6	38.7	31.0	30.3	1.58	40.3	24.7	11.8	1.26
	6-18	41.3	28.3	30.3	1.41	46.9	25.8	11.7	1.03
	18-30	42.7	24.3	33.0	1.53	42.3	25.9	12.9	1.03
	30-42	38.7	24.3	37.0	1.68	36.6	26.1	15.1	1.03
Fargo	0-9	14.1	39.1	47.0	1.20	54.7	37.0	18.3	0.13
	9-14	10.8	36.4	52.9	1.30	50.9	34.5	17.8	0.13
	14-19	8.9	44.3	47.0	1.30	50.9	27.5	14.3	0.13
	19-25	6.7	46.3	47.1	1.40	47.2	25.9	13.4	0.13
	25-39	4.1	48.7	47.3	1.45	45.3	28.7	13.9	0.13
	39-70	5.5	66.6	28.0	1.40	47.2	24.1	7.4	0.13
Hegne	0-9	21.7	38.0	40.4	1.20	54.7	31.9	13.9	0.13
	9-20	10.0	49.5	40.6	1.30	50.9	26.8	11.5	0.13
	20-35	3.7	57.2	39.2	1.45	45.3	28.5	12.4	0.13
	35-45	6.4	59.8	33.9	1.45	45.3	26.9	11.5	0.13
	45-48	72.8	21.3	6.0	1.60	39.6	9.8	3.3	0.13
	49-65	1.6	24.3	74.2	1.50	43.4	42.3	17.3	0.13
Ulen	0-6	47.3	33.7	19.0	1.38	47.8	25.9	19.0	4.00
	6-18	56.7	37.0	6.3	1.37	48.4	8.6	4.7	4.00
	18-30	38.7	40.3	21.0	1.28	51.7	17.0	10.6	4.00
	30-42	9.3	39.0	51.7	1.37	48.4	42.0	30.6	1.60

[§] FC=*field capacity*; PWP=*permanent wilting point*; Drain P.=*drainable porosity*; BD= *bulk density*; Ks=*saturated hydraulic conductivity*

2.7 Model Calibration

A crude "calibration" was performed with the model using the Bearden soil in the undrained condition as a baseline, to set the overall magnitude of runoff/ET prediction for each location. Monthly potential ET coefficients and surface storage were adjusted to produce a long-term average annual water yield (surface runoff) of approximately 4 inches. The 30-year (1961-1990) average annual runoff for the Red River of the North Basin (USDA-NRCS, 1992, Hydrology Guide for Minnesota) shows 2 to 4 inches of runoff annually, for the region (see Appendix, Figure A2). After the calibration, parameter values were not changed for subsequent model runs for the different drain spacings and soils. This coarse calibration in no way implies that the 4.0-inch

long-term annual runoff is precisely what would be expected from the Bearden soil: it is merely a way for roughly apportioning runoff and ET.

Table 4. Drainage spacings (ft) used in the DRAINMOD simulations. Drainage depths of 3.0, 3.5, and 4.0 ft were simulated for all drain spacings.

Soil	Drain Spacing (ft)			
Bearden	132	114	95	76
Borup	437	377	316	255
Colvin	132	114	95	76
Fargo	36	31	26	21
Hegne	36	31	26	21
Ulen	218	188	157	126

Table 5. Example of drainage depth x spacing and resulting daily drainage rates for the Bearden soil.

	Drain Spacing (ft)			
Drain Depth (ft)	**132**	**114**	**95**	**76**
3.0	*0.125 in/day*			
3.5				
4.0				*0.5 in/day*

3 Results

The DRAINMOD model produces a suite of ouputs describing the hydrologic and crop performance characteristics of the modeling scenario of interest. Results are output at the daily, monthly, and annual time scales. The following sections present and describe the results of the 234 modeling scenarios over various time scales.

3.1 Long-term Annual Simulation Results

Tables 6, 7, and 8 present a summary of the long-term mean annual simulation results, displaying the results for the highest and lowest drainage rates (0.5 and 0.125 in/day, respectively), one intermediate drainage rate, and the undrained condition. Each table presents the results for one simulation location and all soils. The reader is referred to Tables A1 through A9 in the Appendix, which display the mean annual simulated drainage and surface runoff volumes, and relative crop yields for all modeling scenarios.

Table 6. Simulated long-term (1913-2011) evapotranspiration (ET), subsurface drainage (DRAIN), surface runoff (RO), water yield = runoff + drainage (W-Yld), and relative crop yield (C-Yld) for four drainage conditions and six soils Crookston, MN. Crop yield is % of maximum yield.

Drain Spacing *(ft)*	Drain Depth *(ft)*	DC *(in/day)*	PRECIP *(in)*	INFIL *(in)*	ET *(in)*	DRAIN *(in)*	RO *(in)*	W-Yld *(in)*	C-Yld *(%)*
Bearden									
UD	**UD**	**UD**	20.5	16.6	16.6	0.0	3.9	3.9	59.2
132	**3.0**	**0.125**	20.5	18.4	16.3	2.1	2.2	4.3	91.3
95	**3.5**	**---**	20.5	18.7	16.2	2.6	1.8	4.4	95.4
76	**4.0**	**0.5**	20.5	19.0	16.1	2.9	1.6	4.5	96.2
Borup									
UD	**UD**	**UD**	20.5	16.8	16.8	0.0	3.8	3.8	56.8
437	**3.0**	**0.125**	20.5	19.2	16.7	2.5	1.3	3.8	89.2
316	**3.5**	**---**	20.5	19.8	16.7	3.1	0.7	3.8	97.0
255	**4.0**	**0.5**	20.5	20.1	16.7	3.4	0.4	3.8	98.8
Colvin									
UD	**UD**	**UD**	20.5	16.8	16.8	0.0	3.7	3.7	53.7
132	**3.0**	**0.125**	20.5	19.7	16.7	3.1	0.8	3.9	99.1
95	**3.5**	**---**	20.5	20.0	16.6	3.4	0.5	3.9	98.7
76	**4.0**	**0.5**	20.5	20.1	16.5	3.6	0.5	4.1	98.2
Fargo									
UD	**UD**	**UD**	20.5	16.7	16.7	0.0	3.8	3.8	56.8
36	**3.0**	**0.125**	20.5	17.9	16.4	1.5	2.6	4.1	77.8
26	**3.5**	**---**	20.5	18.6	15.9	2.6	2.0	4.6	92.7
21	**4.0**	**0.5**	20.5	18.9	15.9	3.0	1.6	4.6	94.8
Hegne									
UD	**UD**	**UD**	20.5	16.3	16.3	0.0	4.2	4.2	51.4
36	**3.0**	**0.125**	20.5	17.9	15.8	2.1	2.6	4.7	83.5
26	**3.5**	**---**	20.5	18.2	15.6	2.6	2.3	4.9	90.9
21	**4.0**	**0.5**	20.5	18.5	15.6	2.9	2.1	5.0	92.6
Ulen									
UD	**UD**	**UD**	20.5	16.8	16.8	0.0	3.7	3.7	57.9
218	**3.0**	**0.125**	20.5	18.9	16.7	2.2	1.6	3.8	96.1
157	**3.5**	**---**	20.5	19.4	16.7	2.7	1.1	3.8	98.7
126	**4.0**	**0.5**	20.5	19.6	16.7	3.0	0.9	3.9	99.0

Table 7. Simulated long-term (1913-2011) evapotranspiration (ET), subsurface drainage (DRAIN), surface runoff (RO), water yield = runoff + drainage (W-Yld), and relative crop yield (C-Yld) for four drainage conditions and six soils Fergus Falls, MN. Crop yield is % of maximum yield.

Drain Spacing *(ft)*	Drain Depth *(ft)*	DC *(in/day)*	PRECIP *(in)*	INFIL *(in)*	ET *(in)*	DRAIN *(in)*	RO *(in)*	W-Yld *(in)*	C-Yld *(%)*
Bearden									
UD	**UD**	**UD**	23.8	20.0	20.0	0.0	3.9	3.9	61.1
132	**3.0**	**0.125**	23.8	21.8	19.1	2.8	2.0	4.8	86.1
95	**3.5**	**---**	23.8	22.3	18.8	3.5	1.6	5.1	90.3
76	**4.0**	**0.5**	23.8	22.6	18.7	3.9	1.3	5.2	90.9
Borup									
UD	**UD**	**UD**	23.8	20.2	20.3	0.0	3.6	3.6	62.8
437	**3.0**	**0.125**	23.8	22.4	20.2	2.2	1.5	3.7	89.2
316	**3.5**	**---**	23.8	23.0	20.2	3.0	0.8	3.8	96.2
255	**4.0**	**0.5**	23.8	23.4	20.1	3.3	0.5	3.8	97.7
Colvin									
UD	**UD**	**UD**	23.8	20.2	20.3	0.0	3.6	3.6	64.6
132	**3.0**	**0.125**	23.8	23.1	19.9	3.3	0.7	3.7	97.1
95	**3.5**	**---**	23.8	23.3	19.6	3.8	0.5	4.3	95.9
76	**4.0**	**0.5**	23.8	23.4	19.4	4.1	0.4	4.5	95.0
Fargo									
UD	**UD**	**UD**	23.8	19.9	20.0	0.0	3.9	3.9	64.0
36	**3.0**	**0.125**	23.8	21.2	18.4	2.7	2.7	5.4	80.2
26	**3.5**	**---**	23.8	21.8	18.3	3.5	2.1	5.6	86.7
21	**4.0**	**0.5**	23.8	22.2	18.2	4.0	1.7	5.7	88.6
Hegne									
UD	**UD**	**UD**	23.8	19.1	19.2	0.0	4.7	4.7	47.8
36	**3.0**	**0.125**	23.8	20.8	18.0	2.8	3.0	5.8	77.2
26	**3.5**	**---**	23.8	21.4	17.9	3.5	2.4	6.0	83.5
21	**4.0**	**0.5**	23.8	21.8	17.8	4.0	2.1	6.1	84.5
Ulen									
UD	**UD**	**UD**	23.8	20.3	20.4	0.0	3.5	3.5	57.9
218	**3.0**	**0.125**	23.8	22.3	20.2	2.1	1.5	3.6	95.1
157	**3.5**	**---**	23.8	22.7	20.2	2.6	1.1	3.7	98.0
126	**4.0**	**0.5**	23.8	23.0	20.1	3.0	0.8	3.8	98.4

Table 8. Simulated long-term (1913-2011) evapotranspiration (ET), subsurface drainage (DRAIN), surface runoff (RO), water yield = runoff + drainage (W-Yld), and relative crop yield (C-Yld) for four drainage conditions and six soils Roseau, MN. Crop yield is % of maximum yield.

Drain Spacing *(ft)*	Drain Depth *(ft)*	DC *(in/day)*	PRECIP *(in)*	INFIL *(in)*	ET *(in)*	DRAIN *(in)*	RO *(in)*	W-Yld *(in)*	C-Yld *(%)*
Bearden									
UD	**UD**	**UD**	20.8	16.9	16.9	0.0	4.0	4.0	62.7
132	**3.0**	**0.125**	20.8	18.8	16.5	2.4	2.0	4.4	89.3
95	**3.5**	**---**	20.8	19.3	16.4	2.9	1.6	4.5	94.3
76	**4.0**	**0.5**	20.8	19.5	16.2	3.2	1.4	4.6	95.2
Borup									
UD	**UD**	**UD**	20.8	17.0	17.0	0.0	3.8	3.8	58.1
437	**3.0**	**0.125**	20.8	19.4	17.0	2.4	1.4	3.8	88.3
316	**3.5**	**---**	20.8	20.1	17.0	3.1	0.7	3.8	96.6
255	**4.0**	**0.5**	20.8	20.4	17.0	3.4	0.4	3.8	98.9
Colvin									
UD	**UD**	**UD**	20.8	17.0	17.0	0.0	3.8	3.8	60.4
132	**3.0**	**0.125**	20.8	20.1	16.9	3.3	0.7	4.0	99.0
95	**3.5**	**---**	20.8	20.3	16.8	3.6	0.5	4.1	98.4
76	**4.0**	**0.5**	20.8	20.5	16.7	3.8	0.3	4.1	97.9
Fargo									
UD	**UD**	**UD**	20.8	17.0	17.0	0.0	3.8	3.8	64.3
36	**3.0**	**0.125**	20.8	18.5	16.3	2.2	2.3	4.5	84.6
26	**3.5**	**---**	20.8	19.0	16.2	2.8	1.8	4.6	92.0
21	**4.0**	**0.5**	20.8	19.3	16.2	3.1	1.5	4.6	94.3
Hegne									
UD	**UD**	**UD**	20.8	16.5	16.5	0.0	4.3	4.3	59.1
36	**3.0**	**0.125**	20.8	18.2	15.9	2.3	2.6	4.9	82.8
26	**3.5**	**---**	20.8	18.7	15.8	2.8	2.2	5.0	90.1
21	**4.0**	**0.5**	20.8	19.0	15.8	3.2	1.8	5.0	92.0
Ulen									
UD	**UD**	**UD**	20.8	17.0	17.0	0.0	3.8	3.8	63.4
218	**3.0**	**0.125**	20.8	19.3	17.0	2.2	1.6	3.8	95.5
157	**3.5**	**---**	20.8	19.7	17.0	2.7	1.1	3.8	98.9
126	**4.0**	**0.5**	20.8	20.0	17.0	3.1	0.8	3.9	99.6

A number of characteristics are apparent upon examination of the long-term mean annual results, which appear to be independent of modeling location. Mean annual subsurface drainage volumes increase with increasing drainage depth and decreasing drainage spacing. These results are anticipated because both increased drainage depth and decreased drainage spacing serve to increase the drainage rate or intensity, for a given soil and location. Mean

annual subsurface drainage volumes increased from 15 to 50 percent from the lowest drainage rate of 0.125 in/day to the highest drainage rate of 0.5 in/day, respectively.

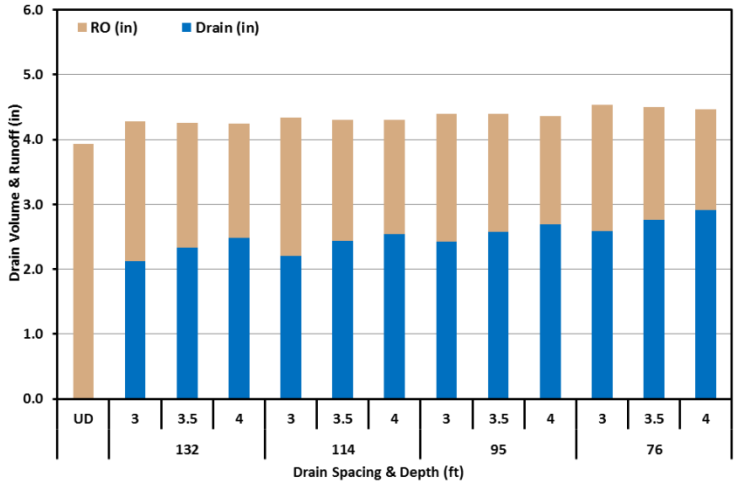
Increases in mean annual drainage volume were accompanied by commensurate decreases in surface runoff volume: increase subsurface drainage volumes mean increased infiltration volumes and hence, decreased surface runoff. The lowest drainage rate of 0.125 in/day decreased mean annual surface runoff volumes from 30 to 80 percent, depending on the combination of soil and location. The highest drainage rates of 0.5 in/day decreased mean annual surface runoff volumes from 55 to 90 percent, depending on soil and location.

Mean annual total water yield, the sum of subsurface drainage and surface runoff (deep seepage was set to zero) is a quantity of particular interest. Mean annual water yields ranged from approximately 4 to 6 inches across all soil, drainage design, and location combinations. Previous modeling results and other modeling research studies have suggested that the introduction of subsurface drainage to poorly drained cropland might increase total water yields. This phenomenon was also observed in this study: long-term mean annual water yields increased for all drained scenarios compared to the undrained baseline for each soil/location combination. Increases in mean annual water yield for the lowest drainage rate of 0.125 in/day ranged from 0 percent (Borup at Crookston) to 38 percent (Fargo at Fergus Falls). Simulated mean annual water yield increased from 0 to 46 percent for the same two soil/location combinations. The average long-term mean annual water yield increase was 9 percent for both Crookston and Roseau, and 21 percent for Fergus Falls. The average long-term mean annual water yield increases for all soils and locations range from 0 to 43 percent, and are displayed in Table 8. Figure 2 illustrates the relationships between mean annual drainage and runoff for drained and undrained conditions, for the Bearden soils at all locations. Graphs for all soils and locations are displayed in the Appendix, Figures A3 through A8.

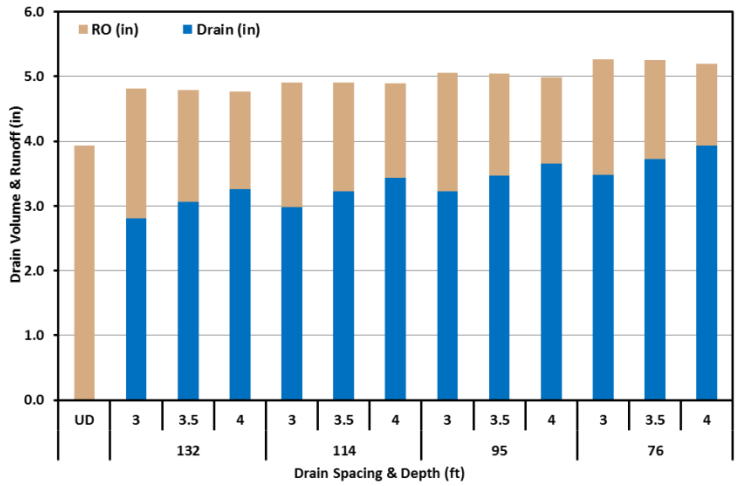
The increases in long-term mean annual water yield with increased subsurface drainage result from reductions in simulated ET for these conditions. Research is currently underway at various universities in the upper Midwest to determine if these decreases in ET under drained conditions are a realistic phenomenon or a modeling artifact. One of the prevailing hypotheses is that annual ET will increase for a healthier, more deeply-rooted crop (under drained conditions), compared to undrained conditions. This hypothesis certainly seems sound for the *transpiration* component of ET, but to what extent the *evaporation* component is affected remains to be seen. Soil evaporation should increase for a wetter soil (undrained) compared to a more well-drained soil.

Table 8. Long-term mean water yield increases (inches and %) for all soils and locations, averaged over all drainage spacing and depths.

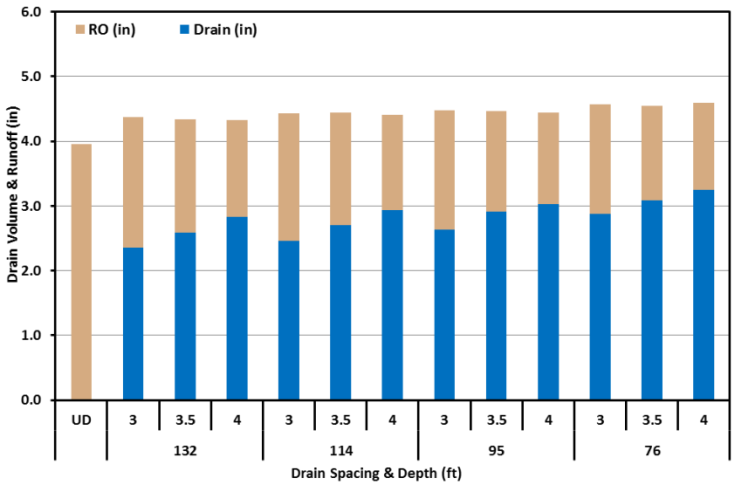
	Crookston		Fergus Falls		Roseau	
Bearden	0.5	13%	1.1	29%	0.5	13%
Borup	0.0	0%	0.2	5%	0.0	0%
Colvin	0.3	7%	0.6	16%	0.3	7%
Fargo	0.6	17%	1.7	43%	0.8	20%
Hegne	0.7	16%	1.3	27%	0.7	16%
Ulen	0.1	4%	0.2	6%	0.0	1%



a.



b.



c.

Figure 2. Simulated long-term mean surface runoff and drainage volumes for the Bearden soil at a) Crookston, b) Fergus Falls, and c) Roseau, MN.

Figure 3 displays the simulated long-term mean relative yield for the six soils, for Crookston, MN. Simulated relative yields for the other locations can be found in Figures A7 and A8, in the Appendix. It should be noted that these simulations were conducted without any calibration for crop yield, so care should be taken in interpreting these results (and not over-interpreting the results). The influence of drainage depth is evident in Figure 3, with deeper drainage depths (and higher drainage rates) outperforming shallower drainage depths. Figure 3 (and the model output from the other two locations – Table A1 through A9 in the Appendix) also suggests that, with a few exceptions, there may be diminishing gains from installing drains at narrower drain spacings.

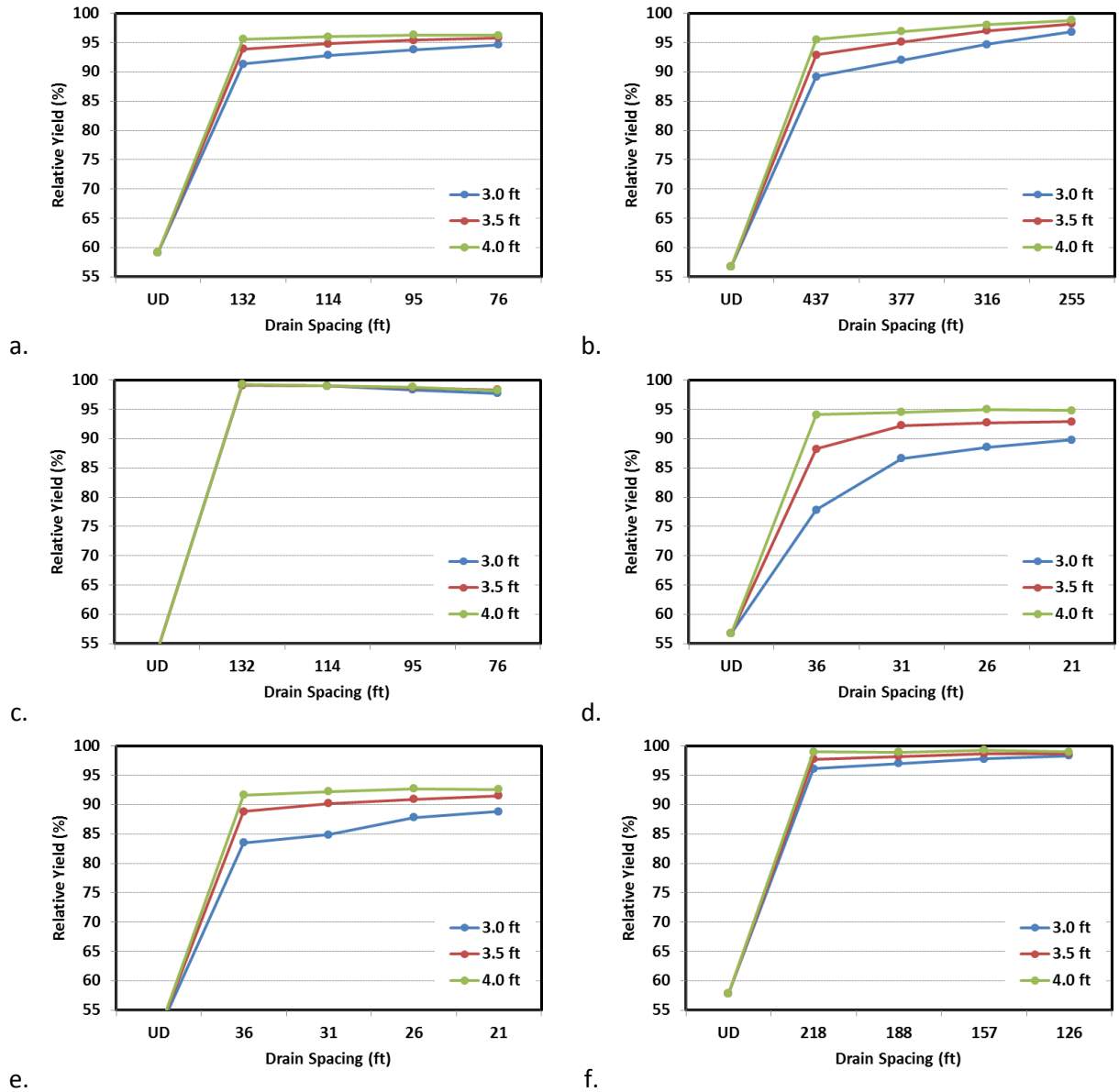
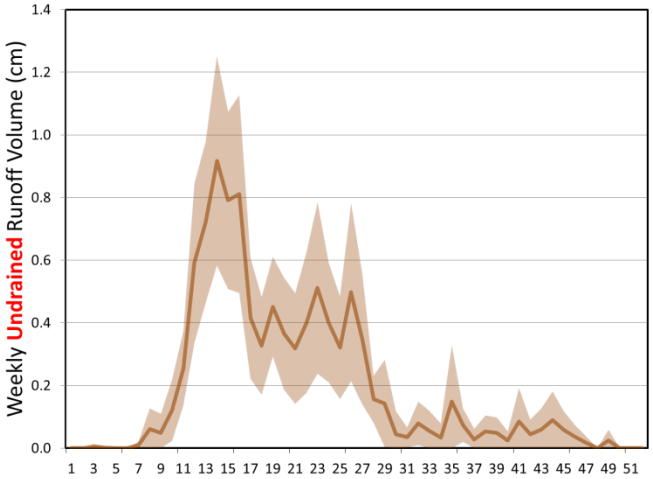


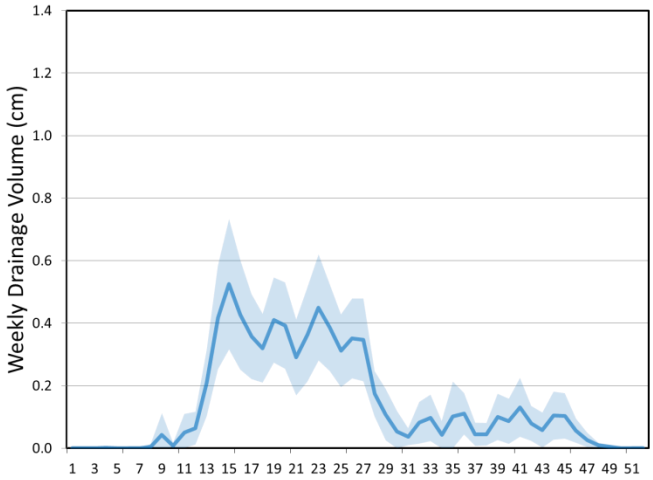
Figure 3. Long-term mean annual relative crop (corn) yield for Crookston, MN for a) Bearden, b) Borup, c) Colvin, d) Fargo, e) Hegne, and f) Ulen soils for the 1913 – 2011 simulation period.

3.2 Long-term Weekly Simulation Results

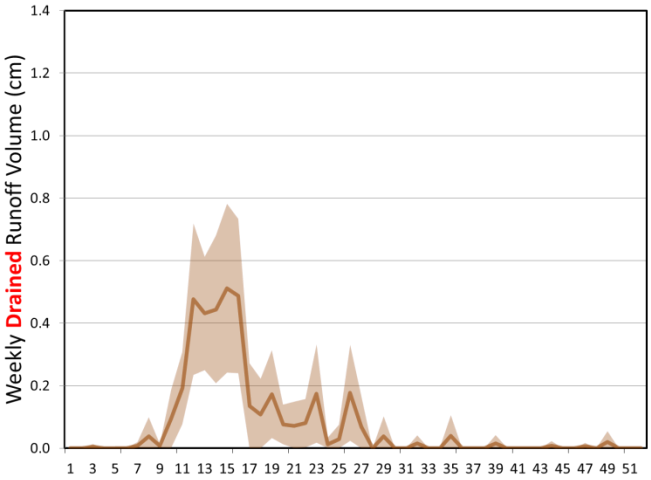
Long-term mean weekly simulation results are displayed in Figures 4 and 5. These figures elucidate the weekly distribution of weekly surface runoff (pre- and post-drainage) and subsurface drainage volumes. These figures illustrate the reduction in surface runoff that occurs with the introduction of subsurface drainage.



a.



b.



c.

Figure 4. Simulated long-term mean weekly a) surface runoff pre-subsurface drainage; b) subsurface drainage, and; c) surface runoff post-subsurface drainage (cm) for the Bearden soil at Crookston.

Figure A10 and A11 in the Appendix present similar curves for the Fargo soil at both Fergus Falls and Roseau.

Figure 5 serves to illustrate the change in predicted weekly water yield from pre- and post-subsurface drainage scenarios. The drainage and post-drainage surface runoff curves (brown and blue) must be added to produce the simulated mean weekly water yield for the Bearden soil at Crookston (red curve). The dashed (black) curve is the water yield pre-drainage, which is simply the surface runoff curve, as previously shown in Figure 4. Figure 5 shows that for the Bearden soil at Crookston, the model predicts, on average, an additional 0.2 cm (.08 in) of water in week 14 and about half that in week 15 of the year (early to mid-April). Similarly, increased mean weekly water yields of roughly 0.1 cm are predicted in weeks 18, 19, and 23.

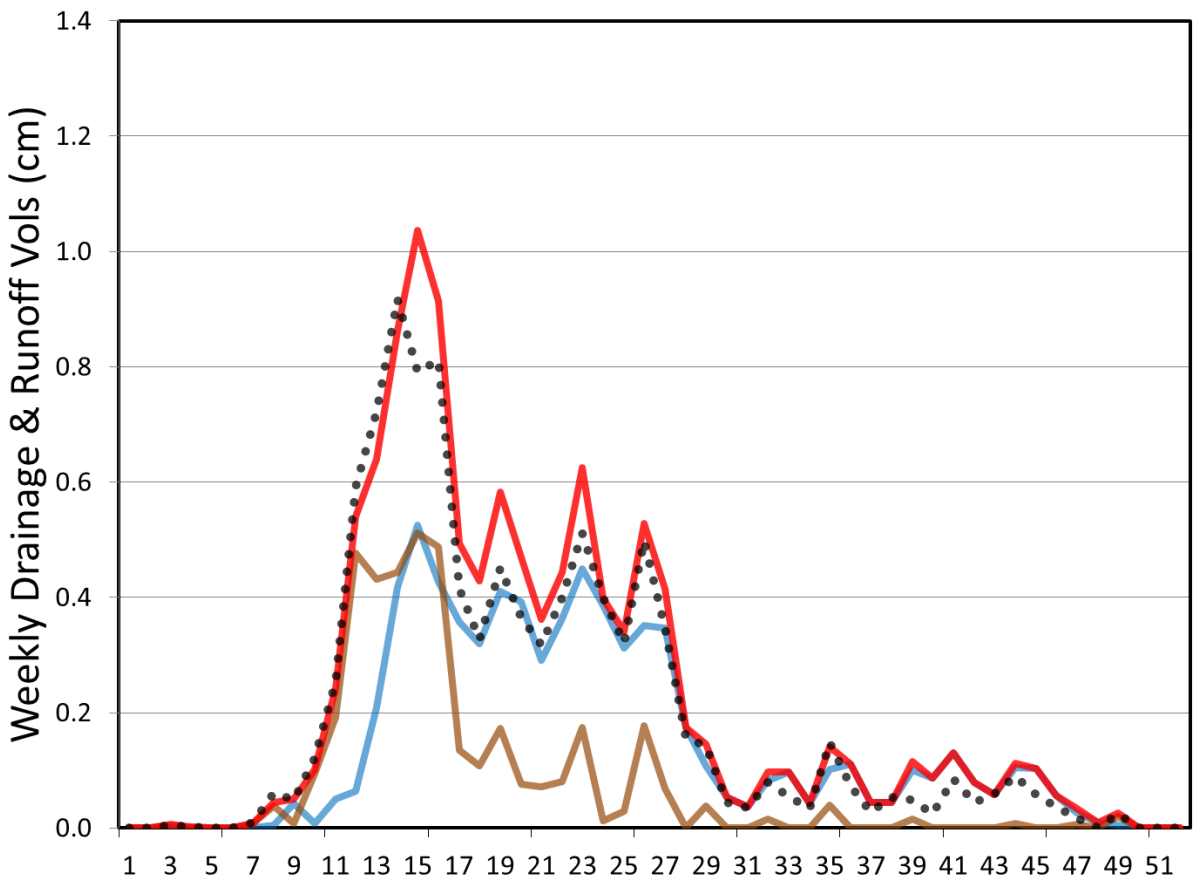
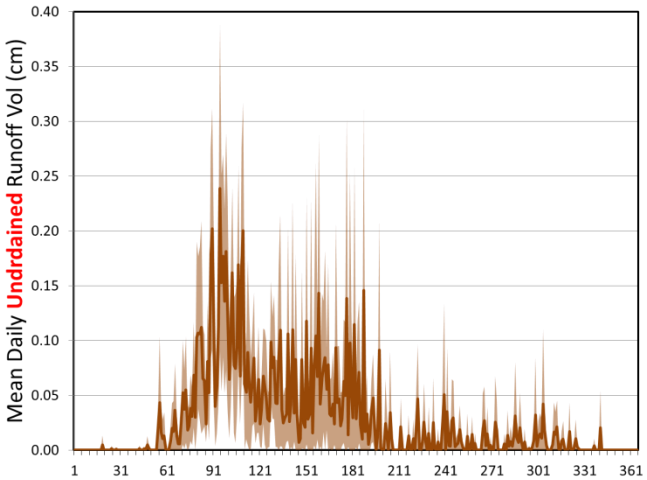


Figure 5. Simulated long-term mean *weekly* drainage and surface runoff (blue and brown lines), weekly water yield (red) and pre-drainage water yield (dashed) for the Bearden soil at Crookston.

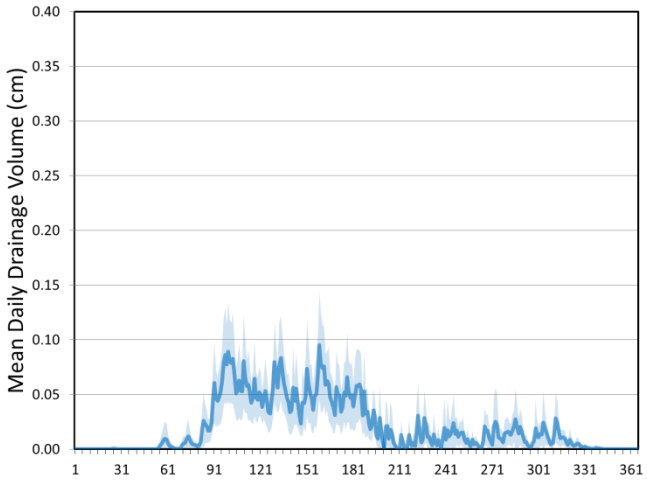
3.3 Long-term Daily Simulation Results

Figures 6 and 7 display long-term mean daily results for the Bearden soil at Crookston. As in the weekly graphs, these graphs illustrate the reduction in mean daily surface runoff with the introduction of subsurface drainage. Water yield for the undrained modeling scenario is simply equal to surface runoff, in Figure 6a. For the post-drainage scenario to obtain water yield, we must add the drainage and runoff curves shown in Figure 6b and c, displayed in larger form in Figure 7a. The result is the red water yield curve displayed in Figure 7b. The black curve in Figure 6b is the undrained water yield (surface runoff). By plotting the two curves together, we see that they overlap to a great degree, with a few instances where the post-drainage water

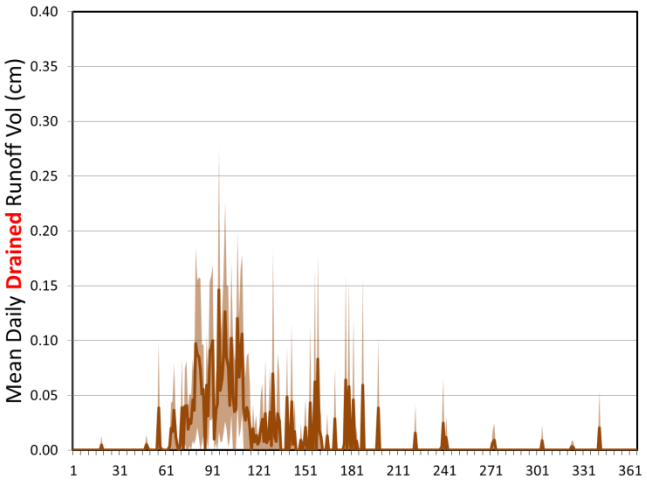
yield is greater and a few instances where the pre-drainage water yield is greater. Because these are mean daily flows, the values are quite small.



a.

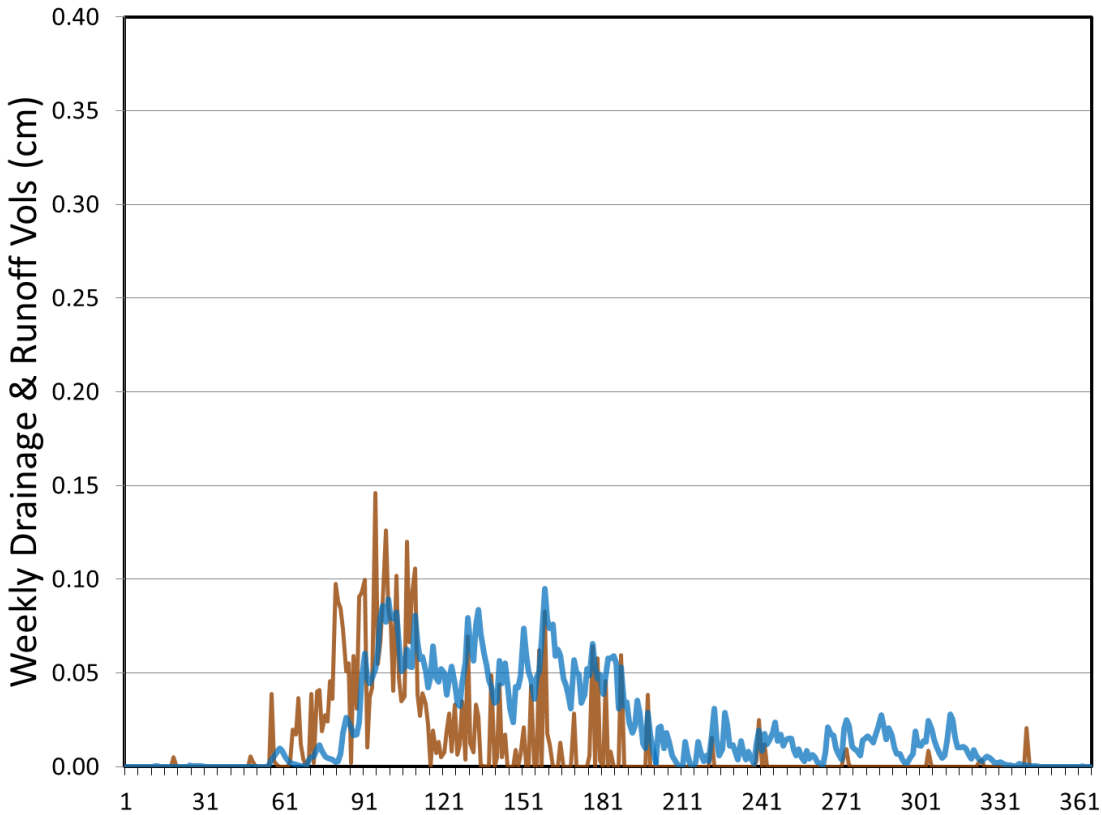


b.

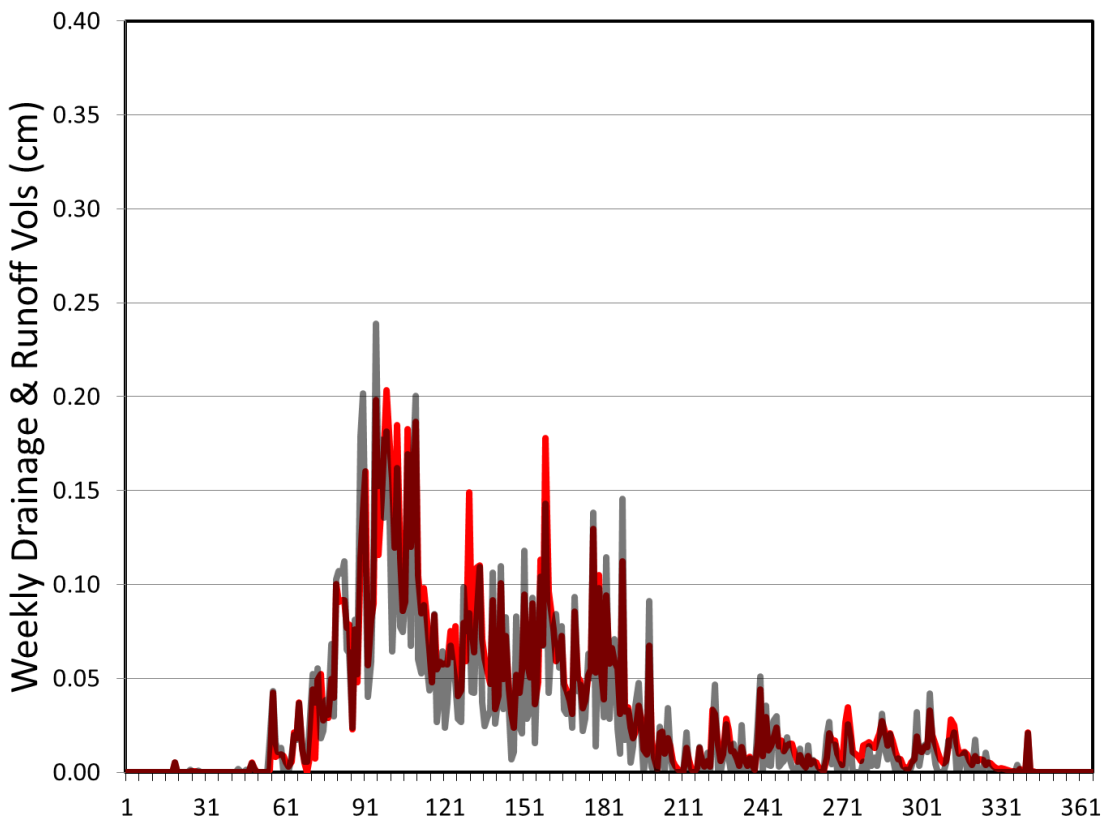


c.

Figure 6. Simulated long-term mean *daily* a) surface runoff with subsurface drainage; b) subsurface drainage, and; c) surface runoff post-subsurface drainage (cm).



a.



b.

Figure 7. a) Simulated long-term mean *daily* drainage and surface runoff (blue and brown lines), and b) *daily* water yield (red) and pre-drainage water yield (gray) in cm.

Figure 8 shows the curves from Figure 5b on a cumulative basis, which gives us more insight into when the additional water yield takes place, during the season, for the Bearden soil at Crookston. The reader is reminded that these curves represent the 99-yr mean of these quantities. The mean annual pre-drainage water yield for this scenario is approximately 10 cm (3.9 in) and the post-drainage water yield (drainage + runoff) is approximately 11.3 cm (4.4 in). We see from Figure 5 that the two curves begin to diverge at around 115 days (Apr 25) and at day 150 (May 30) water yield for the post-drainage scenario out-yielded the pre-drainage scenario by about 0.6 cm (0.25 in). 40 percent of the annual water yield has occurred, at this point (on average). At around day 220 (Aug 8) the post-drainage scenario out-yields the pre-drainage scenario by approximately 1 cm (0.4 in). The remainder of the excess water yield (an additional 0.3 cm) appears to occur after late October.

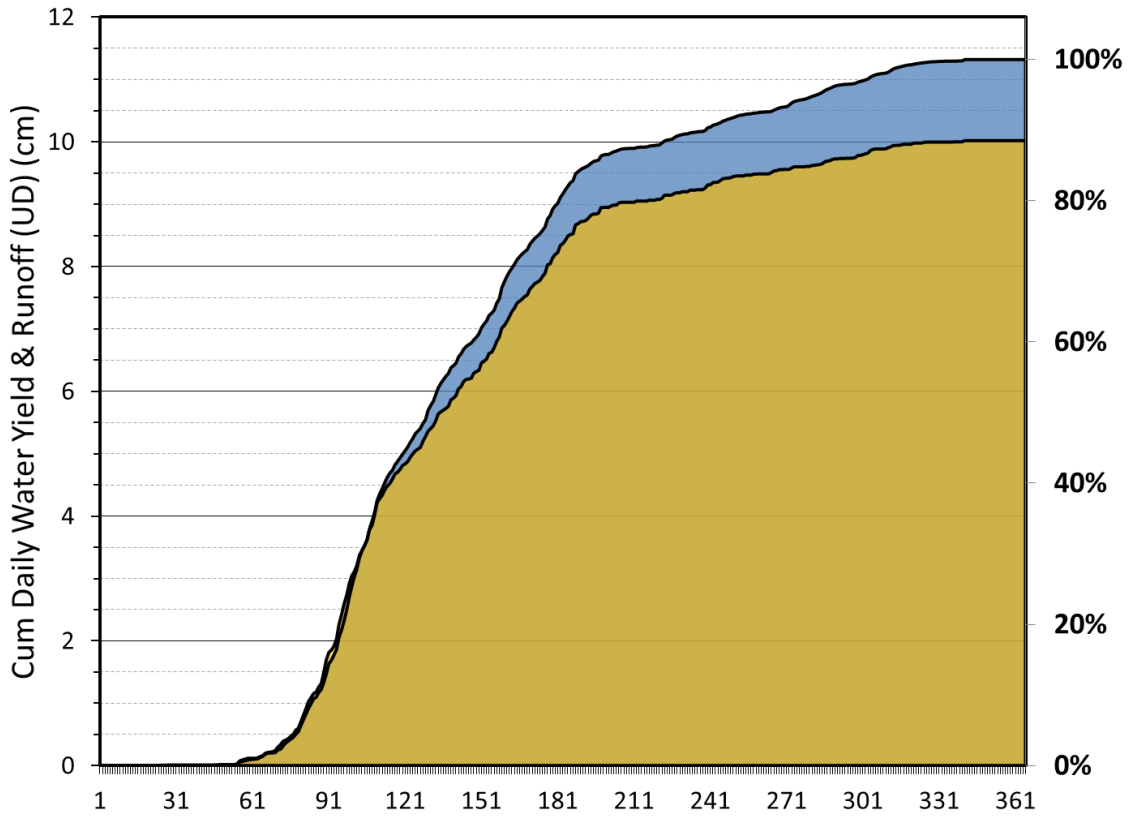
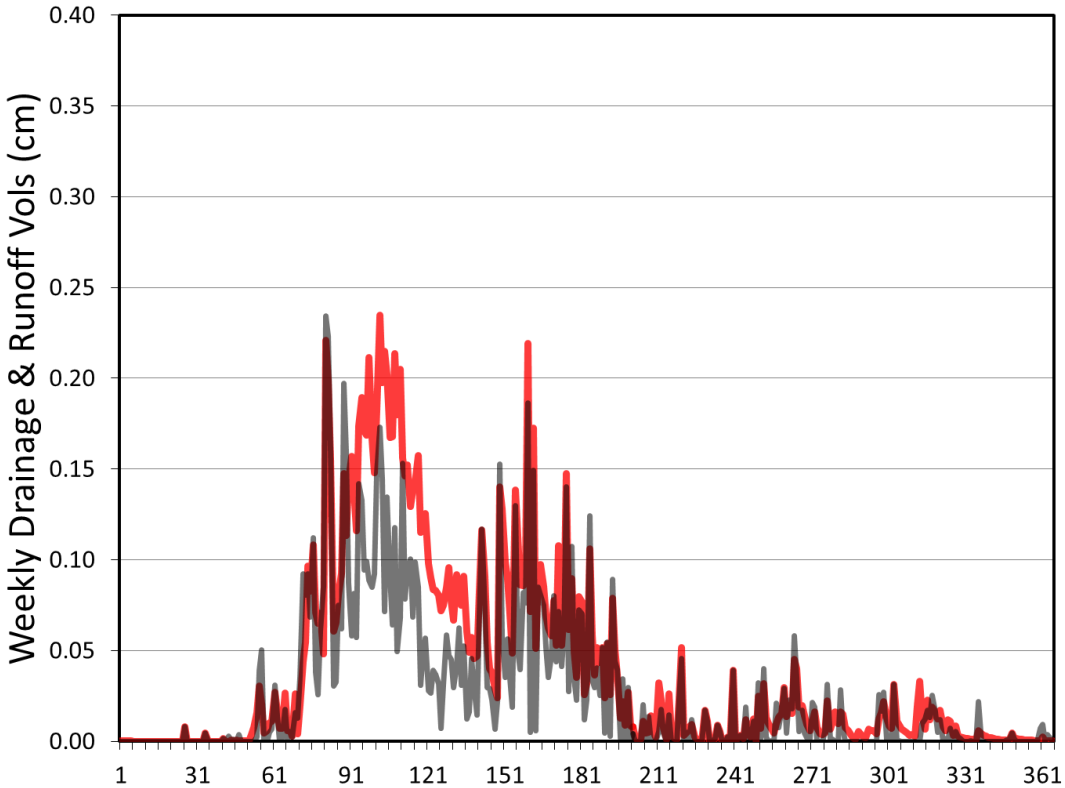
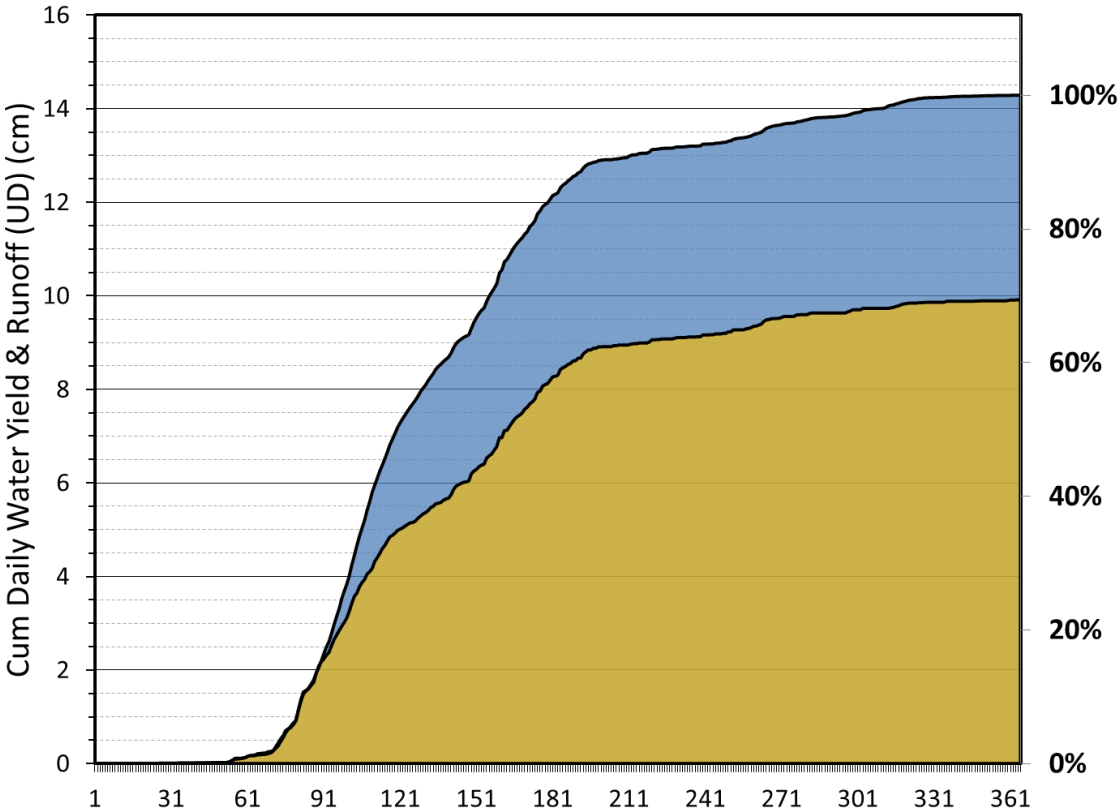


Figure 8. Simulated cumulative mean (99-yrs) daily water yield (cm) (blue curve) for a 0.5 in/day drainage rate (left vertical axis) and percent (right vertical axis), and cumulative pre-drainage surface runoff (brown curve) for the Bearden soil at Crookston, MN.

Figures 9a and 9b present the curves of Figures 5b and 6, for the Fargo soil at Fergus Falls. Recall from Table 8 that Fergus Falls exhibited the largest post-drainage increases in simulated mean annual water yield and moreover, the Fargo soil exhibited an average 43% increase in water yield, post-drainage. The simulated average annual pre-drainage surface runoff for the Fargo soil at Fergus Falls was 10 cm (3.9 in) whereas the combined drainage-surface runoff mean annual water yield for the 0.5 in/day drainage rate is 14.3 cm (5.6 in). It is evident from Figure 6a and 6b that most of the post-drainage water yield increases occur between day 90 and day 140 (March 31 through May 20).



a.



b.

Figure 9. Simulated b) *daily* water yield (red) and pre-drainage water yield (gray) in cm, and; b) cumulative mean (99-yrs) *daily* water yield (cm) for a 0.5 drainage rate (left vertical axis) and percent (right vertical axis), and cumulative pre-drainage *daily* surface runoff (brown) for the Fargo soil at Fergus Falls, MN.

4 Conclusions

A number of important conclusions can be made from this work, listed here in no particular order or priority:

1. Crop prices, land values, and climate are all significant driving forces in terms of agricultural practices and specifically, investments in agricultural drainage. The authors assert that we are likely to see a continuation and increase in the demand and adoption of subsurface drainage in the Red River of the North Basin.
2. The computer simulations described herein, while uncalibrated in terms of predicting a crop response to subsurface drainage, show significant reductions in predicted excess water stress and planting delay due to the adoption of subsurface drainage.
3. The modeling exercise performed herein, for the soils and locations of interest, predicts the following general effects from the adoption of subsurface drainage:
    1) Significantly increased crop yields compared to the undrained scenario;
    2) Relatively small increases (and sometime no increase) in crop yield due to reductions in drain spacing, when evaluated from 0.125 to 0.5 in/day drainage rates;
    3) Increased mean subsurface drainage volumes with increasing drainage rates;
    4) Increased mean subsurface drainage volumes with increasing drainage depth;
    5) Decreased mean surface runoff volumes with increasing drainage rates;
    6) Decreased ET with increasing drainage rates;
    7) Increased mean total water yield (drainage + runoff) with increasing drainage rates, beginning from approximately April 1st and continuing through May.
    8) For a given drainage spacing, deeper drainage depth tends to reduce total water yield.
    9) Reduced crop excess water stress with increased drainage depth.
4. For the soils and locations studied herein, and perhaps for many other soils, opportunities likely exist for making choices that balance goals of crop yield and profitability, with water management goals. Achieving these goals requires making prudent choices among drainage rate, drainage spacing, and drainage depth.

Further work is required to extend our understanding of the performance of artificially drained and undrained agricultural landscapes to more soils and locations, and to improve our ability to predict crop yield responses to these practices.

5 Acknowledgement

The investigators wish to acknowledge the support of the Red River Watershed Management Board (of Minnesota), the Red River Joint Water Resource District (of North Dakota), and the U.S. Army Corps of Engineers in the completion of this work.

Appendix

Table A1. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Bearden and Borup soils at Crookston, Minnesota.

Bearden Soil

Drained Volume

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		0.0				
Depth (ft)	**3.0**		2.1	2.2	2.4	2.6
	3.5		2.3	2.4	2.6	2.8
	4.0		2.5	2.5	2.7	2.9

Surface Runoff

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		3.9				
Depth (ft)	**3.0**		2.2	2.1	2.0	1.9
	3.5		1.9	1.9	1.8	1.7
	4.0		1.8	1.8	1.7	1.6

Relative Yield

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		59.2				
Depth (ft)	**3.0**		91.3	92.8	93.8	94.6
	3.5		93.9	94.8	95.4	95.8
	4.0		95.6	96.0	96.3	96.2

Borup Soil

Drained Volume

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		0.0				
Depth (ft)	**3.0**		2.5	2.7	2.8	3.0
	3.5		2.8	3.0	3.1	3.3
	4.0		3.1	3.2	3.3	3.4

Surface Runoff

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		3.7				
Depth (ft)	**3.0**		1.3	1.2	1.0	0.8
	3.5		1.0	0.9	0.7	0.6
	4.0		0.7	0.6	0.5	0.4

Relative Yield

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		56.8				
Depth (ft)	**3.0**		89.2	92.0	94.7	96.8
	3.5		92.9	95.1	97.0	98.2
	4.0		95.5	96.9	98.0	98.8

Table A2. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Colvin and Fargo soils at Crookston, Minnesota.

Colvin Soil

Drained Volume

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		0.0				
Depth (ft)	**3.0**		3.1	3.1	3.2	3.3
	3.5		3.3	3.4	3.4	3.8
	4.0		3.5	3.5	3.5	3.6

Surface Runoff

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		3.7				
Depth (ft)	**3.0**		0.8	0.8	0.8	0.8
	3.5		0.6	0.6	0.5	0.2
	4.0		0.4	0.4	0.4	0.5

Relative Yield

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		53.7				
Depth (ft)	**3.0**		99.1	99.0	98.3	97.7
	3.5		99.1	99.0	98.7	98.3
	4.0		99.3	99.0	98.8	98.2

Fargo Soil

Drained Volume

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		0.0				
Depth (ft)	**3.0**		1.5	2.3	2.5	2.7
	3.5		1.9	2.5	2.6	2.9
	4.0		2.5	2.7	2.8	3.0

Surface Runoff

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		3.8				
Depth (ft)	**3.0**		6.7	5.9	5.6	5.4
	3.5		5.4	5.1	5.0	4.7
	4.0		4.7	4.4	4.3	4.1

Relative Yield

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		56.8				
Depth (ft)	**3.0**		77.8	86.6	88.5	89.8
	3.5		88.2	92.2	92.7	92.9
	4.0		94.1	94.5	95.0	94.8

Table A3. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Hegne and Ulen soils at Crookston, Minnesota.

Hegne Soil

Drained Volume

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		0.0				
Depth (ft)	**3**		2.1	2.3	2.4	2.6
	3.5		2.4	2.5	2.6	2.9
	4		2.5	2.7	2.8	2.9

Surface Runoff

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		4.2				
Depth (ft)	**3.0**		2.6	2.6	2.5	2.4
	3.5		2.4	2.3	2.3	2.2
	4.0		2.2	2.1	2.1	2.0

Relative Yield

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		51.4				
Depth (ft)	**3.0**		83.5	84.9	87.8	88.8
	3.5		88.8	90.2	90.9	91.5
	4.0		91.6	92.2	92.7	92.6

Ulen Soil

Drained Volume

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		0.0				
Depth (ft)	**3.0**		2.2	2.3	2.4	2.5
	3.5		2.6	2.6	2.7	2.8
	4.0		2.9	2.8	2.8	3.0

Surface Runoff

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		3.7				
Depth (ft)	**3.0**		1.6	1.6	1.5	1.4
	3.5		1.3	1.2	1.1	1.1
	4.0		0.9	1.1	1.0	0.9

Relative Yield

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		57.9				
Depth (ft)	**3.0**		96.1	97.0	97.8	98.3
	3.5		97.7	98.2	98.7	98.7
	4.0		99.0	98.9	99.3	99.0

Table A4. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Bearden and Borup soils at Fergus Falls, Minnesota.

Bearden Soil

Drained Volume

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		0.0				
Depth (ft)	**3.0**		2.8	3.0	3.2	3.5
	3.5		3.1	3.2	3.5	3.7
	4.0		3.3	3.4	3.6	3.9

Surface Runoff

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		3.9				
Depth (ft)	**3.0**		2.0	1.9	1.8	1.8
	3.5		1.7	1.7	1.6	1.5
	4.0		1.5	1.5	1.3	1.3

Relative Yield

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		61.1				
Depth (ft)	**3.0**		86.1	87.8	88.4	88.6
	3.5		89.0	89.8	90.3	90.0
	4.0		91.2	91.5	91.6	90.9

Borup Soil

Drained Volume

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		0.0				
Depth (ft)	**3.0**		2.2	2.4	2.7	2.9
	3.5		2.6	2.8	3.0	3.1
	4.0		2.8	3.0	3.2	3.3

Surface Runoff

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		3.6				
Depth (ft)	**3.0**		1.5	1.3	1.1	0.9
	3.5		1.1	1.0	0.8	0.7
	4.0		0.9	0.7	0.6	0.5

Relative Yield

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		62.8				
Depth (ft)	**3.0**		89.2	91.9	94.1	95.8
	3.5		92.3	94.4	96.2	96.7
	4.0		94.7	96.3	97.3	97.7

Table A5. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Colvin and Fargo soils at Fergus Falls, Minnesota.

Colvin Soil

Drained Volume

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		0.0				
Depth (ft)	**3.0**		3.3	3.5	3.6	3.9
	3.5		3.5	3.6	3.8	4.0
	4.0		3.6	3.7	3.9	4.1

Surface Runoff

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		3.6				
Depth (ft)	**3.0**		0.7	0.7	0.7	0.7
	3.5		0.5	0.5	0.5	0.5
	4.0		0.4	0.4	0.4	0.4

Relative Yield

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		64.6				
Depth (ft)	**3.0**		97.1	96.5	95.7	94.4
	3.5		97.2	96.6	95.9	94.7
	4.0		97.3	96.7	96.0	95.0

Fargo Soil

Drained Volume

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		0.0				
Depth (ft)	**3.0**		2.7	3.0	3.3	3.6
	3.5		3.0	3.2	3.5	3.8
	4.0		3.2	3.4	3.7	4.0

Surface Runoff

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		3.9				
Depth (ft)	**3.0**		2.7	2.6	2.5	2.4
	3.5		2.3	2.2	2.1	2.0
	4.0		1.9	1.8	1.7	1.7

Relative Yield

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		64.0				
Depth (ft)	**3.0**		80.2	81.7	82.6	83.0
	3.5		85.7	86.5	86.7	86.0
	4.0		89.1	89.6	89.5	88.6

Table A6. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Hegne and Ulen soils at Fergus Falls, Minnesota.

Hegne Soil

Drained Volume

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		0.0				
Depth (ft)	**3.0**		2.8	3.0	3.2	3.5
	3.5		3.1	3.3	3.5	3.8
	4.0		3.4	3.6	3.8	4.0

Surface Runoff

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		4.7				
Depth (ft)	**3.0**		3.0	3.0	2.8	2.7
	3.5		2.6	2.6	2.4	2.3
	4.0		2.3	2.2	2.2	2.1

Relative Yield

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		47.8				
Depth (ft)	**3.0**		77.2	78.8	80.6	81.5
	3.5		81.7	82.3	83.5	83.4
	4.0		84.3	84.9	85.1	84.5

Ulen Soil

Drained Volume

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		0.0				
Depth (ft)	**3.0**		2.1	2.3	2.4	2.6
	3.5		2.4	2.5	2.6	2.8
	4.0		2.7	2.8	2.9	3.0

Surface Runoff

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		3.5				
Depth (ft)	**3.0**		1.5	1.4	1.4	1.3
	3.5		1.2	1.2	1.1	1.1
	4.0		1.0	0.9	0.9	0.8

Relative Yield

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		69.3				
Depth (ft)	**3.0**		95.1	96.1	96.7	97.0
	3.5		96.8	97.7	98.0	97.8
	4.0		98.2	98.6	98.6	98.4

Table A7. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Bearden and Borup soils at Roseau, Minnesota.

Bearden Soil

Drained Volume

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		0.0				
Depth (ft)	**3.0**		2.4	2.5	2.6	2.9
	3.5		2.6	2.7	2.9	3.1
	4.0		2.8	2.9	3.0	3.2

Surface Runoff

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		4.0				
Depth (ft)	**3.0**		2.0	2.0	1.8	1.7
	3.5		1.7	1.7	1.6	1.5
	4.0		1.5	1.5	1.4	1.3

Relative Yield

		Spacing (ft)				
		UD	**132**	**114**	**95**	**76**
		62.7				
Depth (ft)	**3.0**		89.3	90.8	92.6	93.5
	3.5		92.3	93.0	94.3	94.7
	4.0		93.8	94.5	95.4	95.2

Borup Soil

Drained Volume

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		0.0				
Depth (ft)	**3.0**		2.4	2.6	2.8	3.0
	3.5		2.7	2.9	3.1	3.2
	4.0		3.0	3.2	3.3	3.4

Surface Runoff

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		3.8				
Depth (ft)	**3.0**		1.4	1.2	1.0	0.9
	3.5		1.1	0.9	0.8	0.6
	4.0		0.8	0.6	0.5	0.4

Relative Yield

		Spacing (ft)				
		UD	**437**	**377**	**316**	**255**
		58.1				
Depth (ft)	**3.0**		88.3	91.2	94.2	96.5
	3.5		91.9	94.3	96.6	98.0
	4.0		94.5	96.5	98.1	98.9

Table A8. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Colvin and Fargo soils at Roseau, Minnesota.

Colvin Soil

Drained Volume

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		0.0				
Depth (ft)	**3.0**		3.3	3.3	3.4	3.5
	3.5		3.4	3.4	3.6	3.7
	4.0		3.5	3.6	3.7	3.8

Surface Runoff

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		3.8				
Depth (ft)	**3.0**		0.7	0.7	0.6	0.7
	3.5		0.5	0.5	0.5	0.5
	4.0		0.4	0.4	0.4	0.3

Relative Yield

		Spacing (ft)				
		UD	**131**	**113**	**94**	**75**
		60.4				
Depth (ft)	**3.0**		99.0	98.8	98.3	97.6
	3.5		99.1	98.9	98.4	97.7
	4.0		99.1	98.9	98.5	97.9

Fargo Soil

Drained Volume

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		0.0				
Depth (ft)	**3.0**		2.2	2.4	2.6	2.8
	3.5		2.4	2.6	2.8	3.0
	4.0		2.6	2.7	2.9	3.1

Surface Runoff

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		3.8				
Depth (ft)	**3.0**		2.3	2.2	2.2	2.0
	3.5		2.1	1.9	1.8	1.8
	4.0		1.8	1.7	1.6	1.5

Relative Yield

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		64.3				
Depth (ft)	**3.0**		84.6	86.5	88.3	89.9
	3.5		89.5	90.9	92.0	92.4
	4.0		92.4	93.4	94.1	94.3

Table A9. Simulated long-term mean annual drained volume, surface runoff and relative crop yield for the Hegne and Ulen soils at Roseau, Minnesota.

Hegne Soil

Drained Volume

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		0.0				
Depth (ft)	**3.0**		2.3	2.4	2.6	2.8
	3.5		2.5	2.7	2.8	3.0
	4.0		2.7	2.9	3.1	3.2

Surface Runoff

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		4.3				
Depth (ft)	**3.0**		2.6	2.5	2.4	2.3
	3.5		2.3	2.2	2.1	2.0
	4.0		2.1	2.0	1.9	1.8

Relative Yield

		Spacing (ft)				
		UD	**36**	**31**	**26**	**21**
		59.1				
Depth (ft)	**3.0**		82.8	85.5	87.3	89.4
	3.5		87.9	89.1	90.1	90.8
	4.0		90.4	91.3	91.4	92.0

Ulen Soil

Drained Volume

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		0.0				
Depth (ft)	**3.0**		2.2	2.3	2.5	2.6
	3.5		2.5	2.6	2.7	2.8
	4.0		2.8	2.8	2.9	3.1

Surface Runoff

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		3.8				
Depth (ft)	**3.0**		1.6	1.5	1.4	1.2
	3.5		1.2	1.2	1.1	1.0
	4.0		1.0	1.0	0.9	0.8

Relative Yield

		Spacing (ft)				
		UD	**218**	**188**	**157**	**126**
		63.4				
Depth (ft)	**3.0**		95.5	96.2	97.6	98.7
	3.5		97.3	98.1	98.9	99.4
	4.0		98.6	99.2	99.5	99.6

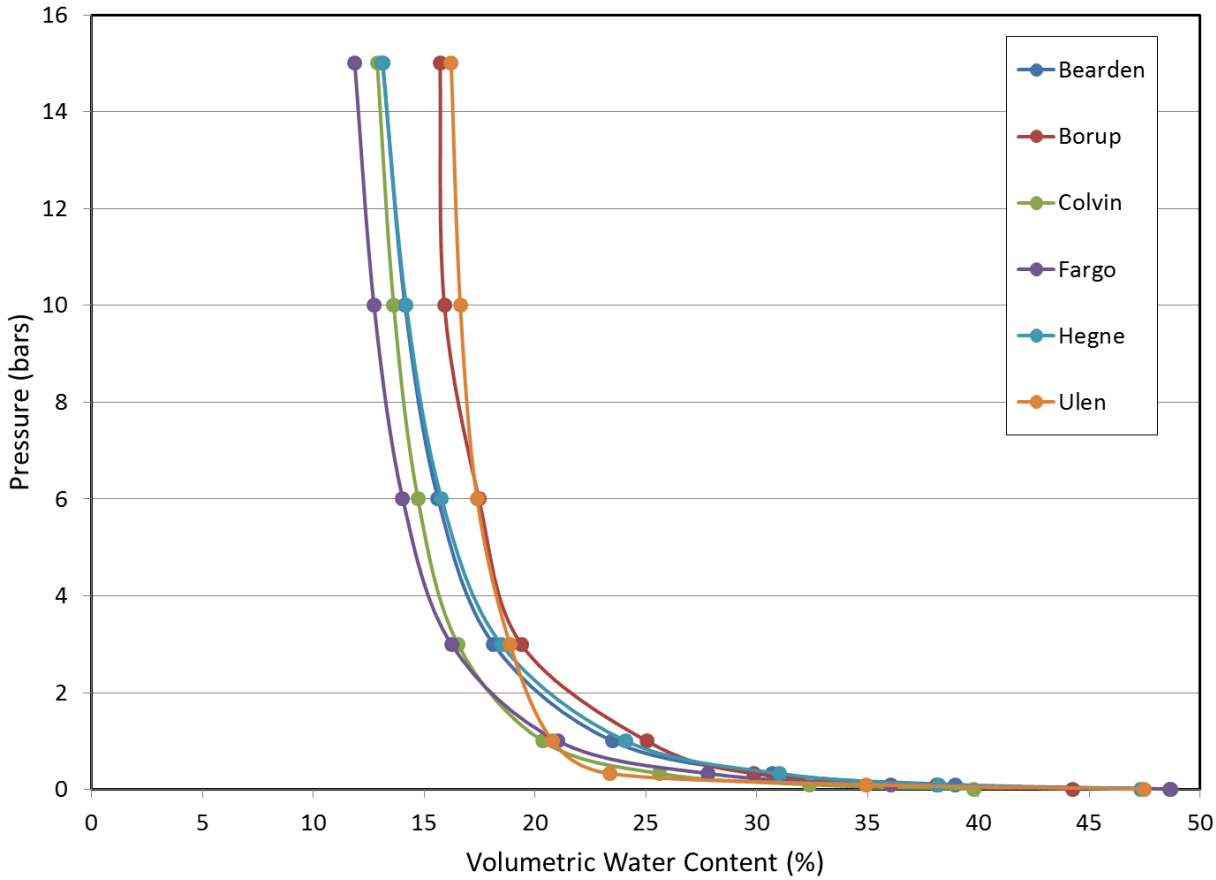


Figure A1. Soil water content versus pressure for the six soils chosen for the study. Soil moisture at wilting point corresponds to 15 bars of pressure and soil moisture at field capacity occurs at 0.33 bars.

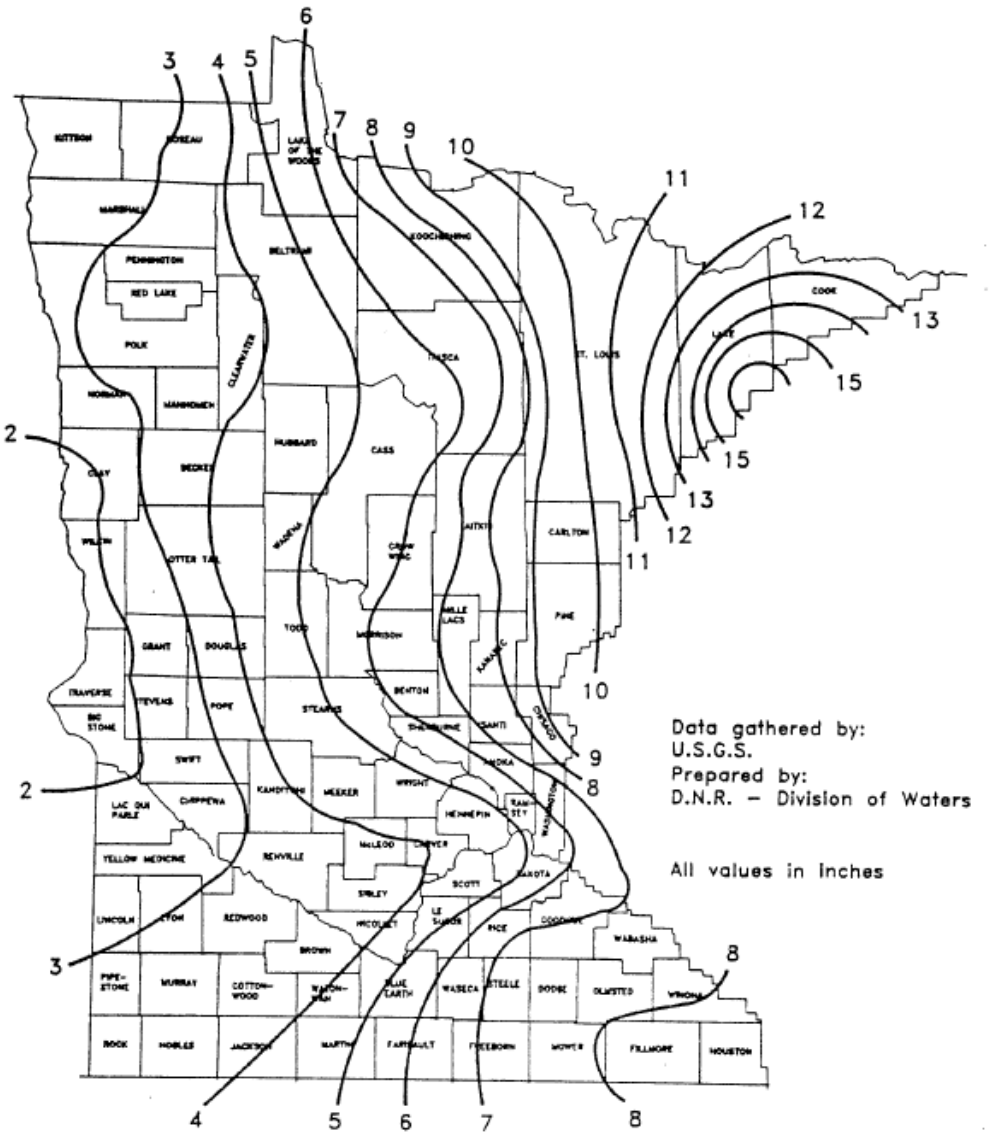
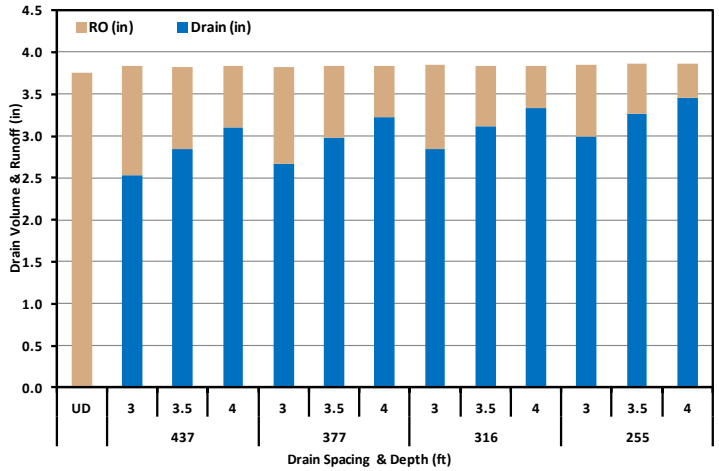
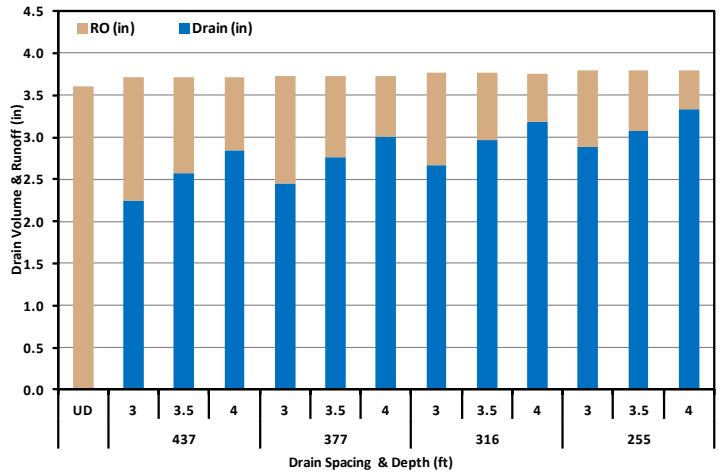


Figure A2. 30-yr (1961-1990) average annual runoff in inches (USDA-NRCS-MN, 1992)[16].

[16] USDA-NRCS-MN. 1992. Hydrology Guide for Minnesota: Getting the most out of your raindrop.



a.



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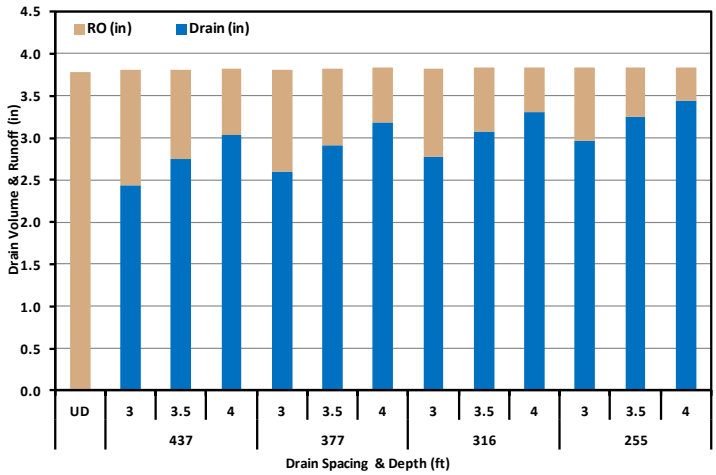
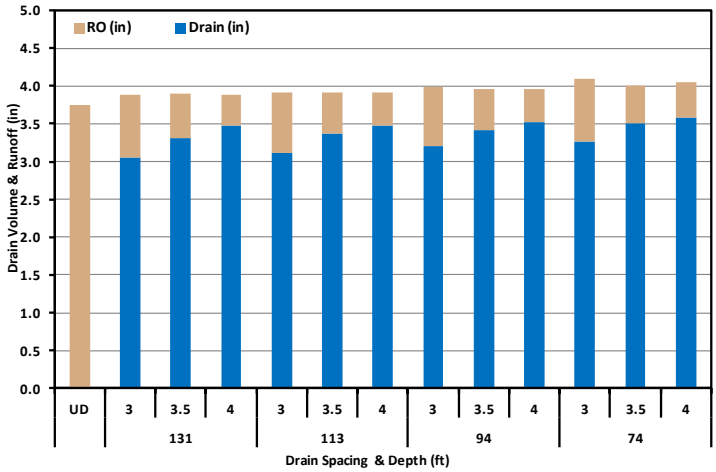


c.

Figure A3. Simulated long-term mean surface runoff and drainage volumes for the Borup soil at a) Crookston, b) Fergus Falls, and c) Roseau, MN.



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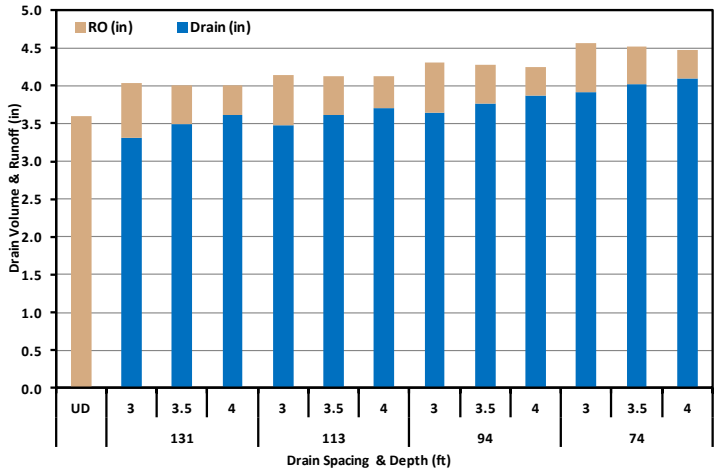

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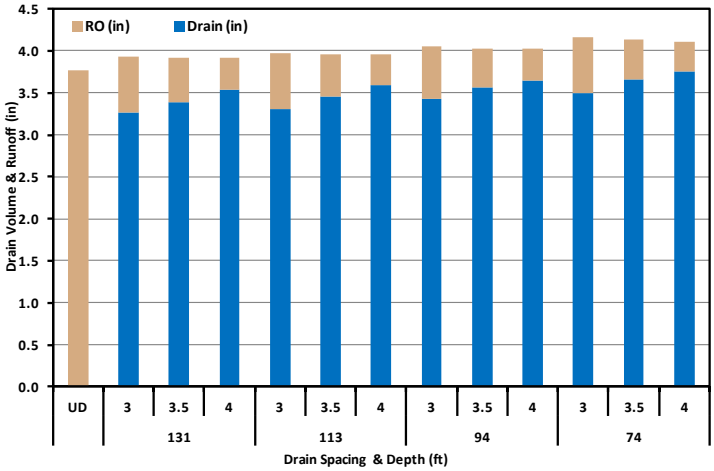
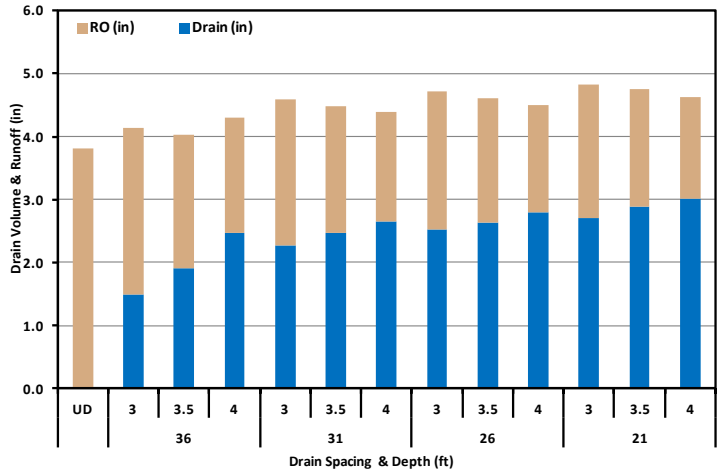


c.

Figure A4. Simulated long-term mean surface runoff and drainage volumes for the Colvin soil at a) Crookston, b) Fergus Falls, and c) Roseau, MN.



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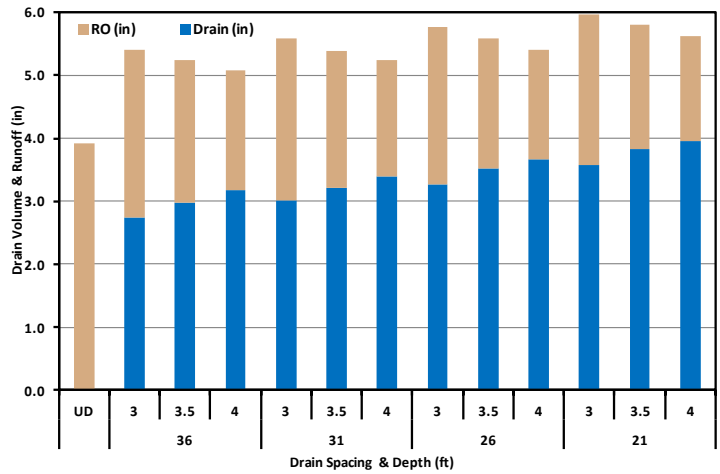

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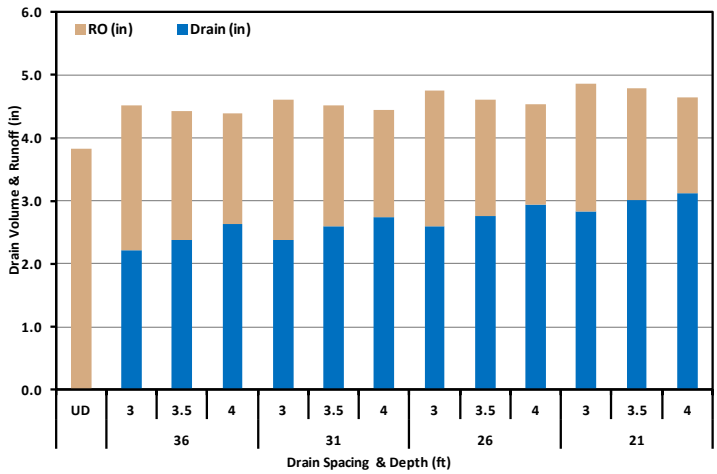
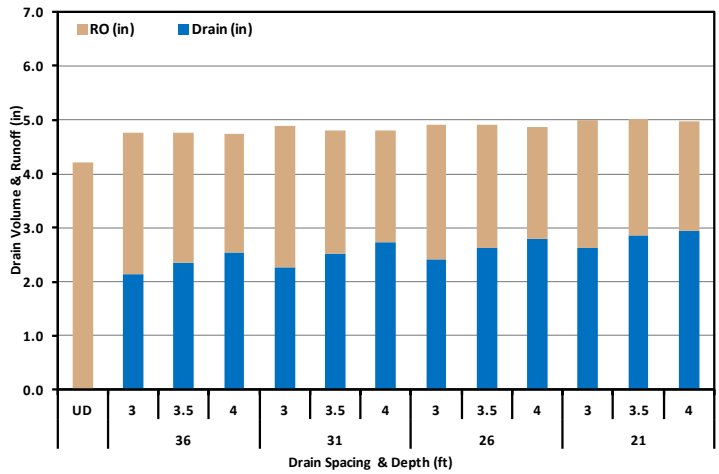


c.

Figure A5. Simulated long-term mean surface runoff and drainage volumes for the Fargo soil at a) Crookston, b) Fergus Falls, and c) Roseau, MN.



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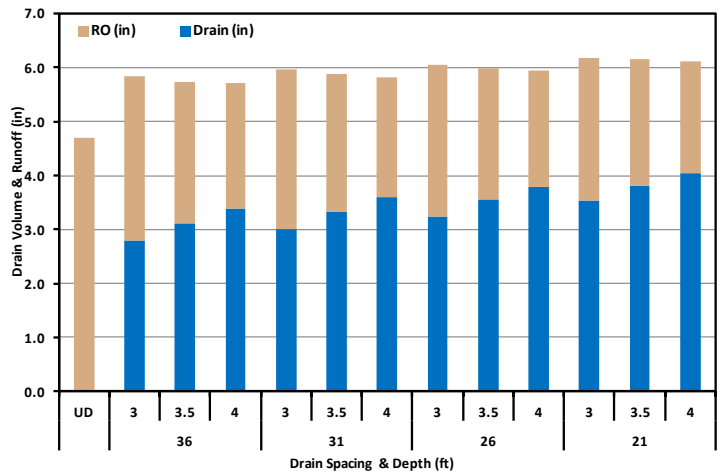

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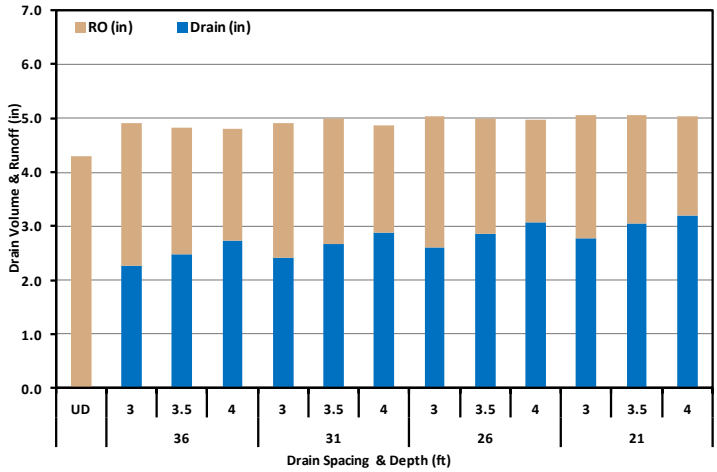
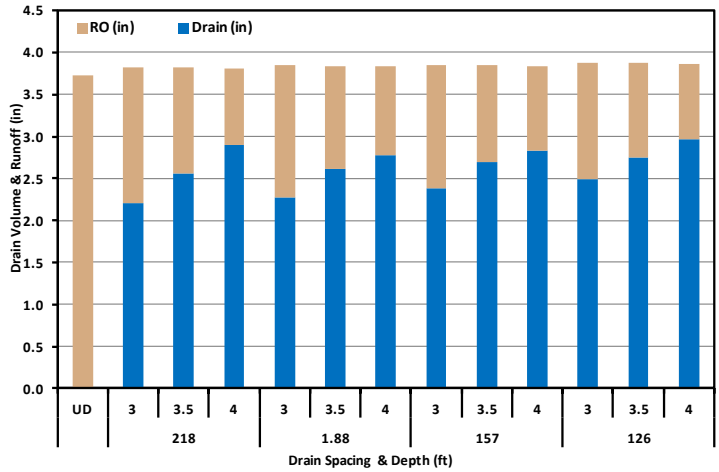


c.

Figure A6. Simulated long-term mean surface runoff and drainage volumes for the Hegne soil at a) Crookston, b) Fergus Falls, and c) Roseau, MN.



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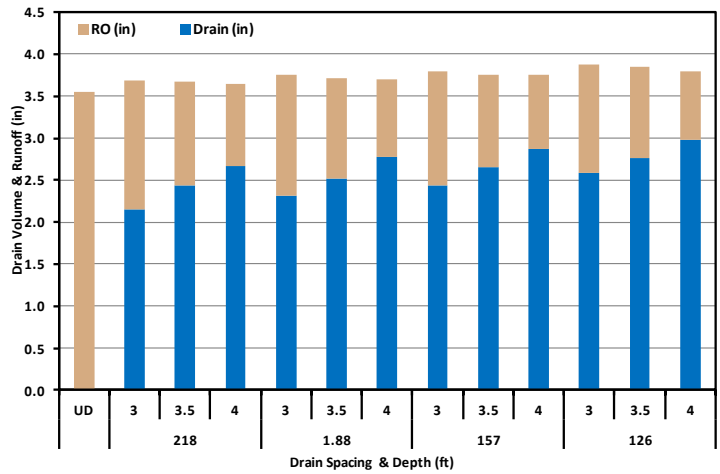

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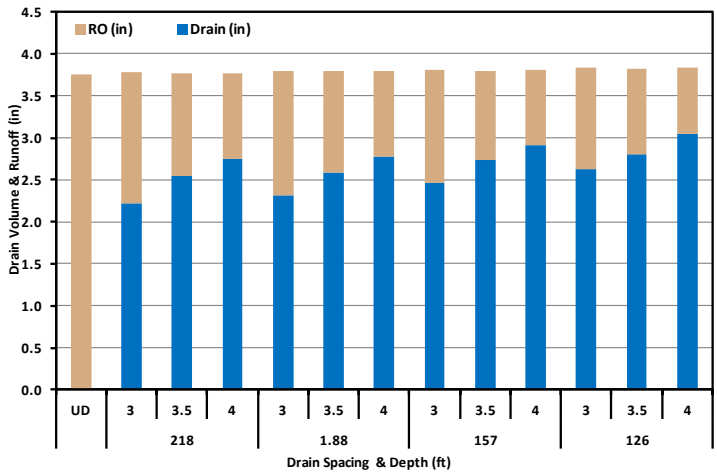


c.

Figure A7. Simulated long-term mean surface runoff and drainage volumes for the Ulen soil at a) Crookston, b) Fergus Falls, and c) Roseau, MN.

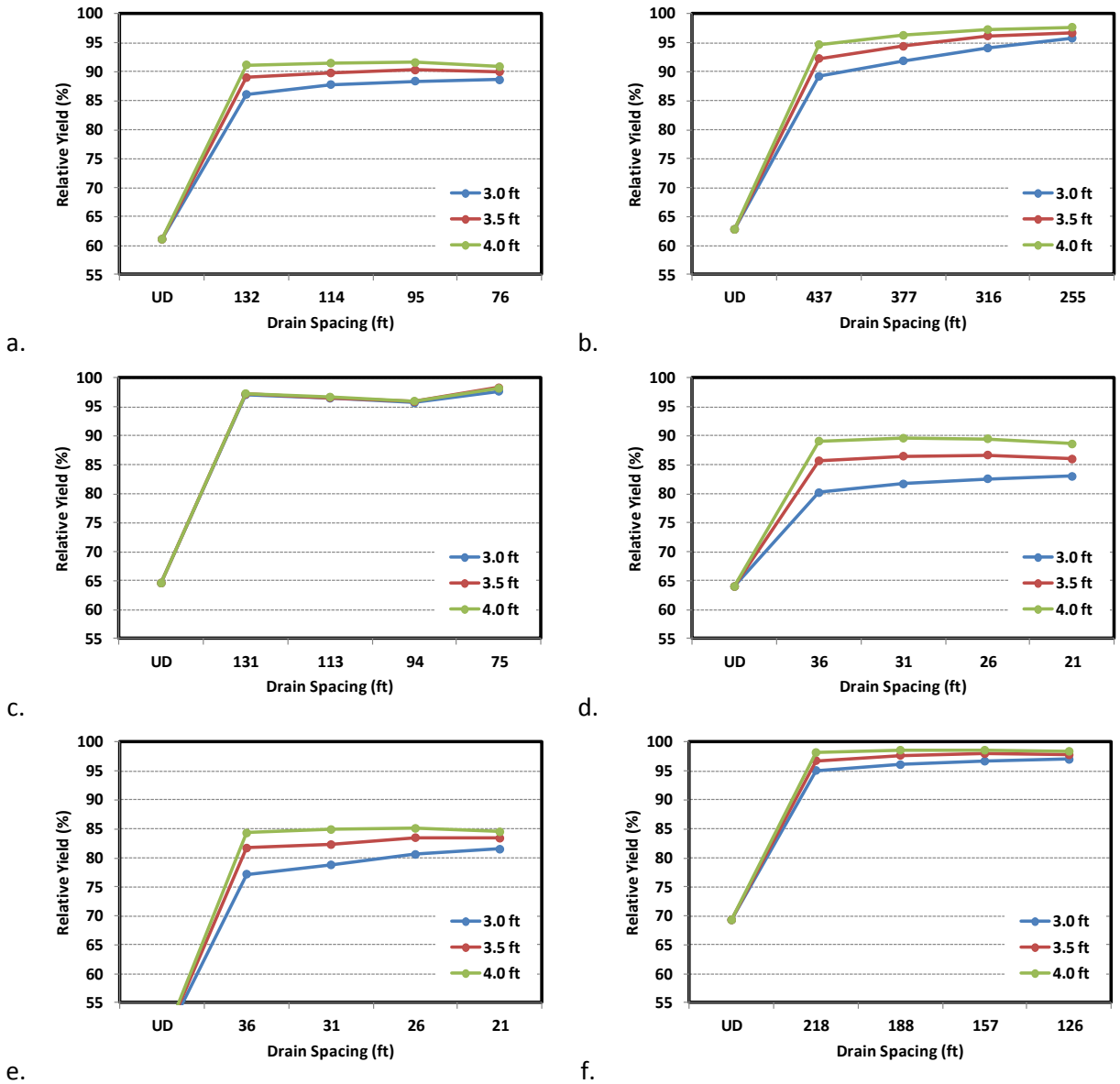


Figure A8. Long-term mean annual relative crop (corn) yield for Fergus Falls, MN for a) Bearden, b) Borup, c) Colvin, d) Fargo, e) Hegne, and f) Ulen soils for the 1913 – 2011 simulation period.

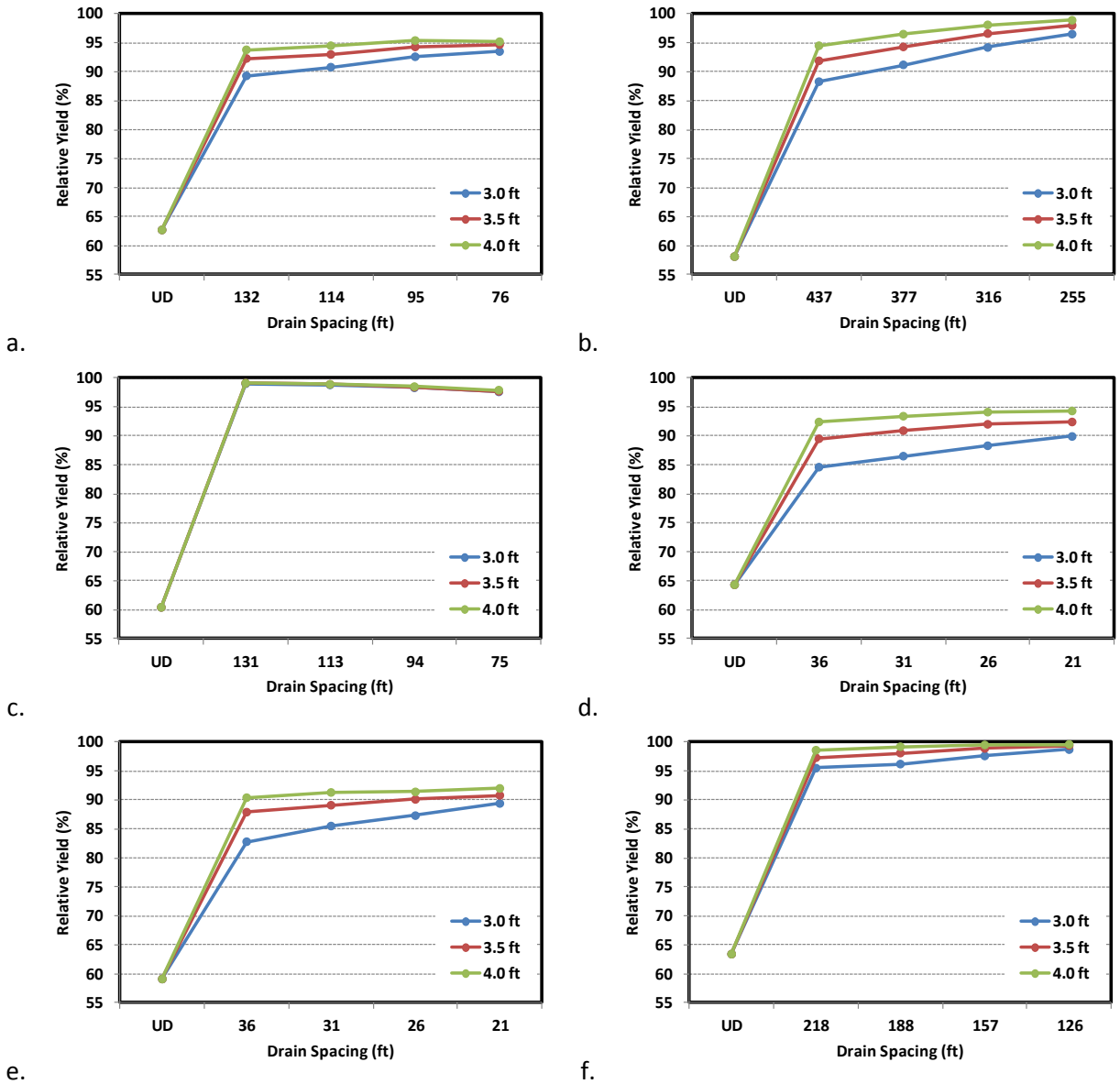
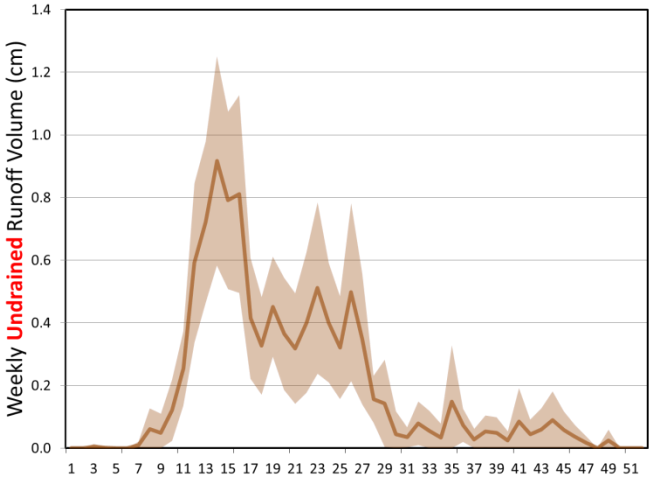
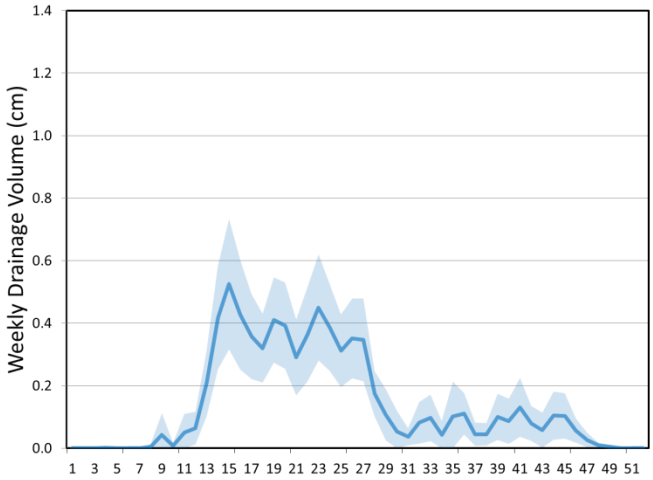


Figure A9. Long-term mean annual relative crop (corn) yield for Roseau, MN for a) Bearden, b) Borup, c) Colvin, d) Fargo, e) Hegne, and f) Ulen soils for the 1913 – 2011 simulation period.



a.



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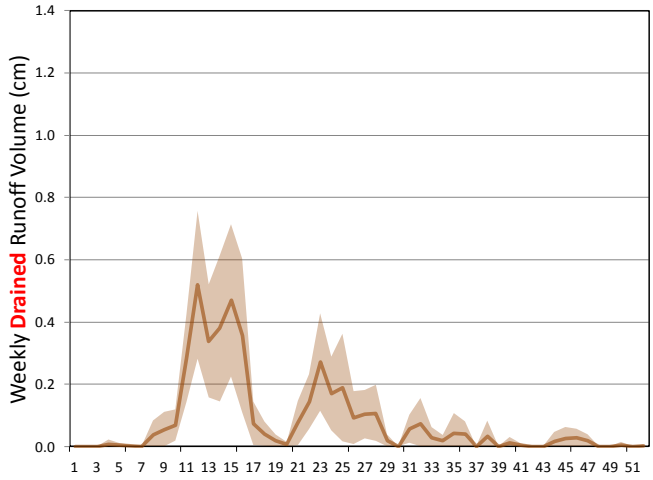
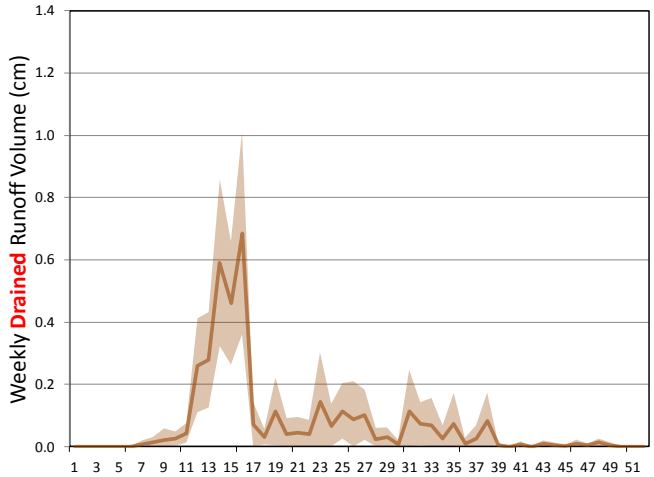
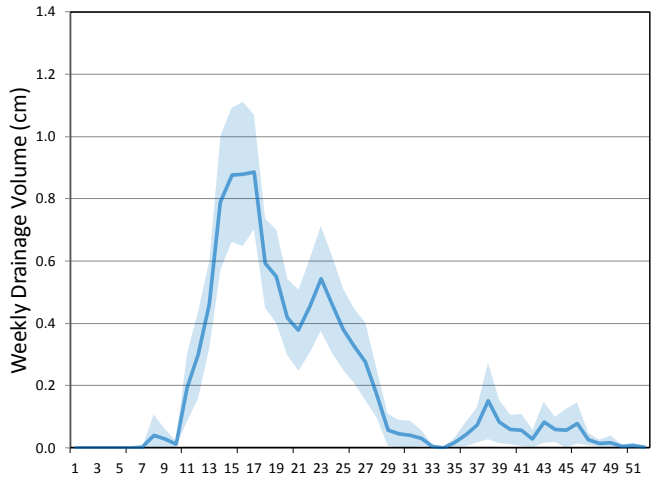


c.

Figure A10. Simulated long-term mean weekly a) surface runoff with subsurface drainage; b) subsurface drainage, and; c) surface runoff post-subsurface drainage (cm) for the Fargo soil at Fergus Falls.



a.



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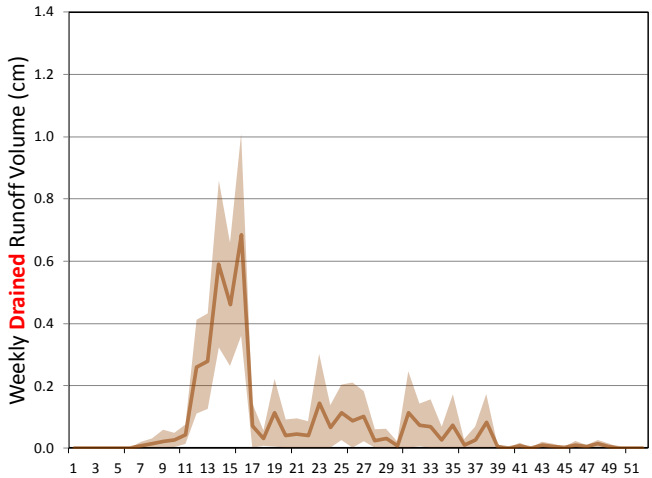

c.

Figure A11. Simulated long-term mean weekly a) surface runoff with subsurface drainage; b) subsurface drainage, and; c) surface runoff post-subsurface drainage (cm) for the Fargo soil at Roseau.