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Assessment of a Large Subsurface Controlled Drainage and Irrigation System: I. Design, Soil Properties, and Water Management

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Abstract: *Controlled subsurface drainage irrigation systems have been designed to promote agronomic performance and to limit overland transport of nutrients during high rainfall events. In this manuscript we describe the design of a 40 ha controlled subsurface drainage irrigation system, describe the soil resource and describe the soil water contents influenced by drainage and irrigation operations. With the use of the Subsurface controlled irrigation/drainage system, crop yields approach regional yield thresholds and soil water contents were maintained between field capacity and the maximum allowed soil water deficit, thus optimizing crop growth and development. In companion manuscripts we describe agronomic performance of corn (Zea mays L.), nutrient uptake patterns, and nutrient concentrations from tile drain effluents and note their potential impact on surface water resources.*

Key Words: *Drainage, Irrigation, Maximum Allowed Water Depletion*

Introduction

Subsurface Controlled Drainage and Irrigation

Irrigation is a land practice that supplies water to the root zone to encourage normal plant functioning, including optimum photosynthesis. Too much water or too little water is detrimental to crop growth. Drainage is a land-management practice designed to remove surplus water to improve land productivity. The design of drainage systems is predicated on soil properties, climate, and producer intentions (Kanwar et al., 1988; Schwab et al., 1975 and 1985; "Design and Construction of Subsurface Drains in Humid Areas.", 1996). Controlled drainage is a form of land drainage where the producer specifies the drainage system's capacity to store excess soil water until drainage is desired. Storing excess soil water limits the leaching of soluble nitrate-N and possibly augments denitrification during the non-cropping season, lessening the nitrate-N impact on receiving surface water bodies. In agriculture, drainage removes gravitational water, which provides: (i) a warmer and more aerated rooting zone, (ii) a more timely farming operation, (iii) a more favorable root respiration capacity, (iv) a greater rooting depth, (v) a more favorable environment for minimizing denitrification, (vi) more soil volume for nutrient uptake, (vii) improved microbial activity and subsequent soil structure attainment, (viii) and reduced erosion attributed to enhanced infiltration capacities (Havlin et al., 2005). The main benefit of irrigation is plant hydration, promoting carbon dioxide assimilation for photosynthesis and herbicide activation.

The purpose of this manuscript is to describe the design and soil water performance of a controlled subsurface drainage and irrigation system. Within this context, the soil resource is described, noting the subsequent soil water distribution and soil water availability for enhancing crop performance. In companion manuscripts soil nutrient availability, nutrient uptake patterns and nutrient effluent transport from drainage tiles are addressed.

Materials and Methods

Design of a Controlled Subsurface Irrigation/Drainage System

The study area, bordering Williams Creek, is a small portion of the Hubble Creek watershed in Cape Girardeau County, Missouri, (X=264770.265, Y=4130996.241, Zone 16) and is located on the Southeast Missouri State University David M. Barton Agriculture Research Center. The study area, called the crop science unit, consists of approximately 40 ha of precision laser-graded land having a controlled subsurface drainage/irrigation system. The controlled subsurface irrigation/drainage system was USDA-NRCS designed and was constructed in 2007.

The soil resource is predominately composed of soils of the Wilbur series (90%) (Coarse-silty, mixed, superactive, mesic Fluvaquentic Eutrudepts) and the Wakeland series (10%) (Coarse-silty, mixed, superactive, nonacid, mesic Aeric Fluvaquents). The Wilbur series consists of deep, moderately permeable, moderately well-drained to somewhat poorly-drained soils having an Ochric – Cambic diagnostic horizon sequence developed in strongly weathered coarse-silty alluvium derived from mixed materials. The Wakeland series exists as small soil pockets within the landscape (0.5 to 1.0 ha) and consists of very deep, somewhat poorly drained soils that formed in silty alluvium. Both soils reside on a floodplain having occasional flooding.

The climate is continental humid. Summers are hot and humid with a mean July temperature of 26°C, whereas winter temperatures are mild, with a mean January temperature of 2°C. The mean annual precipitation of 1.19 m is seasonally distributed, with somewhat greater rainfall in spring (National Cooperative Soil Survey of Cape Girardeau County, Missouri, 1981).

The Controlled Drainage and Irrigation Design

A series of five electric powered wells having submersible pumps collectively supply 0.18 m^3/ha-hr of water for optimum irrigation performance. Water is conveyed from the wells to a 40 ha production field (Crop Science Unit) using underground 20 cm high-pressure PVC irrigation pipe. All drainage/irrigation tiles were placed using a laser-guided tile plow at approximately 1 meter of soil depth. Drainage/irrigation tiles have gradients of 0.1% trending east-west and 0.15% trending north-south. During irrigation, water is conveyed to the center of the field where manifolds with flow regulators and flow gauges disperse the water to each of four equal land areas (Figure 1). Stop-log boxes having adjustable baffles control land drainage and irrigation and are designed to raise or lower the perched water table to a soil root zone depth specified by the producer.

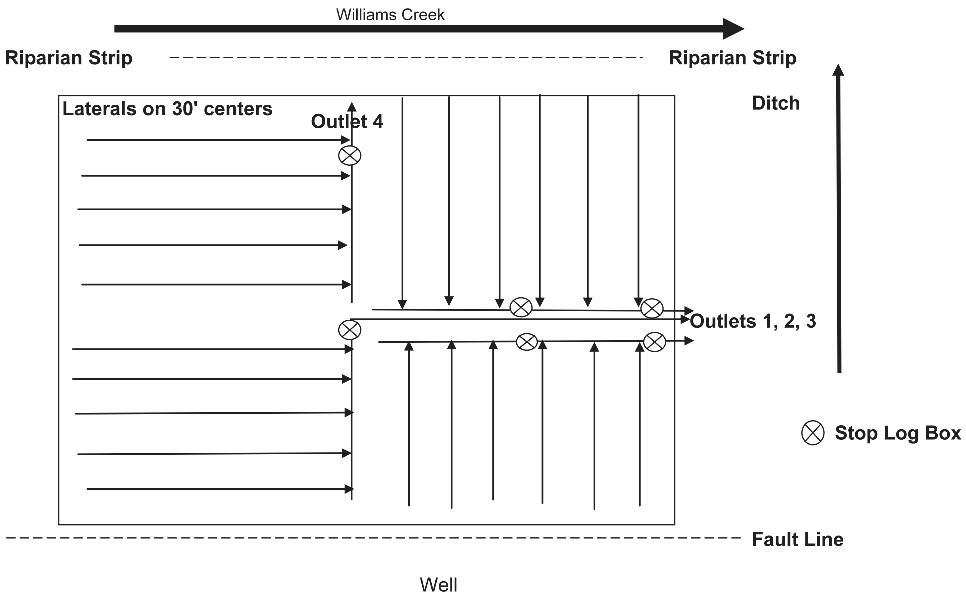
Soil Classification Criteria and Laboratory Analysis

Nine soil profiles were described and sampled in excavated pits by USDA-NRCS personnel using standard USDA-NRCS protocols (Soil Survey Division Staff, 1993). In addition, at two sites a hydraulic soil probe sampled two substrate layers at 4.3–6.1 m and at more than 6.1 m. The underlying substrate consisted of silty clay to silty clay loam materials with a clay separate dominated by smectite.

Field soil water measurement involved water table height estimations using piezometer tubes. Irrigation water rates, rainfall monitoring and gravimetric soil moisture distribution by depth were estimated on a weekly basis. Typically gravimetric soil water contents were obtained by soil augers, weighing and oven drying. Soil sampling depths were 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm. The gravimetric water contents were calculated as: gravimetric water content = (field moist weight – oven dried weight) / oven dried weight. Volumetric water contents were calculated as: volumetric water content = gravimetric water content * (bulk density/specific gravity of water). The bulk density has units of $g\text{-}cm^{-3}$, whereas the specific gravity of water is 1 $g\text{-}cm^{-3}$. Tile drain effluents were qualitatively estimated by soil water content differences over weekly time intervals.

A grid soil sampling protocol was established to provide a perspective of the soil diversity across the crop science unit. One hundred 0.4 ha grids (1 acre grid) were sampled by taking five 15 cm deep (six-inch) cores for bulk mixing to obtain one composite sample. The soil samples were processed at the

Figure 1. Illustration of the drainage design and stop-log box locations.



Fischer University Missouri Delta Research Center (Portageville, Missouri) for pH, total acidity, exchangeable cations, soil organic matter, Bray-I P, DTPA extractable Fe-Mn-Zn-Cu, and sulfate-S.

Air-dried samples from the excavated soil pits were lightly crushed and sieved to separate the fine earth fraction. Soil bulk density was determined by the saran coated clod method and performed by USDA-NRCS personnel. Soil pH in water involved mixing equal volumes of soil and water and also equal volumes of soil and 0.01 M $CaCl_2$, with pH measurement performed using a combination pH electrode. The exchangeable cations (Ca, Mg, K and Na) were estimated using a 1M ammonium acetate (pH 7) extraction followed by elemental analysis using air-acetylene flame atomic adsorption spectroscopy. The total acidity was estimated by titration with 0.01 M NaOH to pH 8.0 (Carter, 1993). The cation exchange capacity (CEC) was estimate by summation of total acidity and the exchangeable bases. The CEC was also determined by ammonium acetate saturation and subsequent measures of exchangeable ammonium (Performed by the University Missouri-Columbia Soil Characterization Laboratory). Soil organic matter contents were estimated by loss on ignition at 450°C (LOI) (Carter, 1993). Bray-1 PO_4-P, NO_3-N and SO_4-S concentrations were determined by the soil testing laboratory of the University Missouri-Columbia Delta Research Center (Portageville, MO).

The clay, silt and sand separates were isolated by Na-saturation of the exchange complex, washing with water-methanol mixtures to remove excess electrolyte, dispersion in Na_2CO_3 (pH 9.2), followed by centrifuge fractionation and wet sieving (Carter, 1993). Soil bulk density was determined by USDA-NRCS personnel using saran-coated shaped clods.

Oriented whole clay (<2 μm) samples were prepared for X-ray diffraction to identify the clay mineralogy. Mg-saturated glycerol-solvated samples were air-dried by sedimentation onto glass-slides, producing oriented mounts. X-ray diffractograms were obtained with a Scintag diffractometer using CuK-alpha radiation. Spectra were scanned from 2 to 30° 2-theta at $0.02° s^{-1}$. Peak areas were used to compare clay mineral differences among soil horizons (Moore and Reynolds, 1989). Peak area was determined after background removal using a curve fitting algorithm associated with Scintag diffraction management system software. Peak positions at 1.8 to 1.77nm, 1.4 to 1.5 nm, 0.99 to 1.01 nm, and 0.71 to 0.72 nm were used to identify smectite, HIM, hydrous mica and kaolinite.

Results

Soil Profile Characterization

Three pedons of the Wakeland series and six pedons of the Wilbur series were classified and characterized; however, only one representative pedon of each series is presented. The Wakeland series consists of very deep, moderately well-drained to somewhat poorly-drained soils that formed in silty alluvium. The pedons have uniform silt loam textures displaying Ap-Bw-Cg horizon sequences (Tables 1 and 2), having moderate medium platy structures in the near surface horizons that typically breaks into weak medium subangular blocky structures in the Bw horizons. The deeper Cg horizons generally show moderate coarse prismatic structures. Sand contents gradually become more abundant on transition to the deeper Cg horizons. The silt ratios show a transition to greater coarse silt contents at the Bw-Cg horizon boundary.

The dominant soil matrix colors are dark gray to dark brown in the A and Bw horizons, transitioning to gray and light brownish gray in the Cg horizons. Iron-Mn accumulations, Fe-depletions and Fe-accumulations are evident throughout the soil profiles, but are more prominent in the Cambic and Cg horizons. Common to many, very fine to fine tubular moderate pores are evident throughout the soil profile. The clay mineralogy is mixed, with hydroxyy-Al interlayered vermiculite slightly more abundant in the near surface horizons and smectite slightly more evident in the Cg horizons.

Soil pH ranges from slightly acid in the near-surface horizons to acid and very strongly acid in the Cg1 to Cg4 horizons (Table 3). The soil organic matter contents range from 1.2 to 0.7 in the A horizons and decline with increasing soil depth. The exchangeable cations are dominated by calcium (Ca), especially in the near-surface soil horizons. Total acidity values range from 3.0 to 5.7 cmol/kg, with slightly smaller total acidity values in the deeper Cg horizons. The CEC is medium (12–18 cmol/kg) in the A and upper Bw horizons and is low (<12 cmol/kg) in the Cg horizons.

The Wilbur pedon consists of a very deep, moderately well-drained soil that formed in silty alluvium. The pedon has uniform silt loam textures throughout the soil profile, displaying an Ap – Bw – C (some of the other pedons displayed Cg horizons at deeper depths). Moderate medium prismatic structures in the near surface horizons part to weak to moderate, medium subangular blocky structures, especially in the Bw horizons. The deeper Cg horizons generally show moderate coarse prismatic structures that alter to weak medium subangular blocky structures. The A horizons show slightly greater ratios of fine silt to total silt, whereas the sand ratio is somewhat uniform throughout the soil profile.

The dominant soil matrix colors are dark brown to dark yellowish brown in the A and Bw horizons, transitioning to light gray, gray, light brownish gray, and grayish brown in the Cg horizons. Iron-Mn accumulations and Fe depletions are evident throughout the soil profiles, especially in the Cambic and Cg horizons. Common to many, very fine to fine tubular moderate pores are evident throughout the soil profile. The clay mineralogy is mixed, with hydroxyy-Al interlayered vermiculite slightly more abundant in the near surface horizons and smectite slightly more evident in the Cg horizons.

Soil pH generally ranges from very strongly acid to strongly acid in the A, Bw and C horizons. The soil organic matter contents range from 0.9 to 0.5 in the Ap and A horizons, then the soil organic matter contents decline with increasing soil

Table 1. Soil profile characterization.

Series	Horizon	Depth (cm)	Structure	Matrix	Boundary
Wakeland	Ap	13	2mpl	10YR 4/3	as
Wakeland	A	25	2mpl to 1msbk	10YR 4/2	as
Wakeland	Bw1	41	2mpl to 1msbk	10YR 4/1	cs
Wakeland	Bw2	56	1fsbk	10YR 4/2	as
Wakeland	Bw3	74	1msbk	10YR 5/2	gw
Wakeland	Cg1	89	2msbk	10YR 6/1	gw
Wakeland	Cg2	104	2cpr	10YR 6/2	gw
Wakeland	Cg3	152	2cpr	10YR 6/2	gw
Wakeland	Cg4	183	2cpr	10YR 6/2	gw
Wakeland	Cg5	203	1cpr	10YR 6/2	—
Wilbur:					
Wilbur	Ap	15	2fpl	10YR 4/3	as
Wilbur	A	28	2mpr to 2msbk	10YR 4/3	cs
Wilbur	Bw1	41	1mpr to 2msbk	10YR 4/4	cs
Wilbur	Bw2	74	1cpr to 1msbk	10YR 4/4	cs
Wilbur	C1	97	1mpr to 1msbk	10YR 5/4	as
Wilbur	C2	124	1mpr to 1msbk	10YR 4/4	gw
Wilbur	C3	145	1cpr	10YR 4/4	aw
Wilbur	C4	170	2cpr	10YR 4/4	—

All horizons have silt loam textures
1 is weak, 2 is moderate, 3 is strong structure
f is fine, m is medium and c is coarse structure
pl is platy, sbk is subangular blocky and pr is prismatic.
As is abrupt smooth; cs is clear smooth; gw is gradual wavy

Table 2. Physical properties of Soil.

Series	Horizon	% Clay	% Silt	% Sand	Silt Ratio£	Sand Ratio¥
Wakeland	Ap	19.1	79.2	1.7	1.2	0.65
Wakeland	A	21.1	76.9	2.0	1.6	0.50
Wakeland	Bw1	18.0	78.9	3.1	1.4	0.48
Wakeland	Bw2	18.0	78.2	3.8	1.5	0.26
Wakeland	Bw3	14.8	82.0	3.2	1.2	0.44
Wakeland	Cg1	9.5	85.8	4.7	0.9	0.60
Wakeland	Cg2	12.2	84.5	3.3	0.7	0.63
Wakeland	Cg3	14.9	75.6	9.5	0.4	0.68
Wakeland	Cg4	13.1	77.2	9.7	0.4	0.73
Wakeland	Cg5	12.7	76.9	10.4	0.4	0.74
Wilbur	Ap	16.3	82.4	1.3	1.4	0.69
Wilbur	A	17.8	80.4	1.8	1.1	0.72
Wilbur	Bw1	16.7	80.1	3.2	0.9	0.69
Wilbur	Bw2	9.7	84.6	5.7	0.5	0.82
Wilbur	C1	8.3	83.3	8.4	0.5	0.79
Wilbur	C2	7.7	83.3	9.0	0.4	0.79
Wilbur	C3	9.7	80.6	9.7	0.5	0.79
Wilbur	C4	8.5	81.3	10.2	0.4	0.75

£ Silt ratio is the ratio of fine silt to coarse silt.
¥ Sand ratio is the ratio of fine sand to total sand.

Table 3. Chemical properties of soil.

	-----cmol/kg-----								
		-----Exchangeable Bases-----						-----pH-----	
Series Horizon		Ca	Mg	Na	K	Acidity CEC	% OC.	$CaCl_2$	Water
Wakeland									
Ap	12.2	1.2	0.1	0.3	5.7	17.2	1.2	6.4	6.9
A	11.9	1.2	0.1	0.5	3.6	16.6	0.7	6.4	6.9
Bw1	9.7	1.2	0.1	0.1	3.8	14.1	0.6	6.1	6.5
Bw2	7.6	0.8	0.1	0.1	5.3	13.3	0.5	5.4	5.8
Bw3	4.8	0.8	0.1	0.1	5.2	11.0	0.3	4.7	5.3
Cg1	1.9	0.4	0.1	0.1	4.1	5.7	0.1	4.2	4.7
Cg2	3.3	1.2	0.2	0.1	4.6	8.8	0.1	4.3	4.8
Cg3	5.6	2.4	0.3	0.1	3.1	10.8	0.1	4.9	5.5
Cg4	5.2	2.5	0.3	0.1	3.0	10.4	0.1	5.1	5.8
Cg5	5.4	2.4	0.3	0.1	3.0	10.5	0.1	5.2	5.9
Wilbur									
Ap	7.2	0.8	0.1	0.2	5.2	12.9	0.9	4.9	5.2
A	8.0	0.8	0.2	0.1	4.6	13.2	0.5	5.2	5.6
Bw1	7.2	0.8	0.2	0.1	4.4	11.4	0.4	5.0	5.4
Bw2	3.9	0.4	0.1	0.1	3.6	6.9	0.2	4.4	4.9
C1	2.1	0.4	0.1	0.1	5.4	6.6	0.1	3.9	4.4
C2	3.1	0.4	0.1	0.1	4.0	6.7	0.1	4.1	4.7
C3	4.6	0.8	0.1	0.1	3.1	7.8	0.1	4.5	5.2
C4	4.8	0.8	0.1	0.1	2.5	7.5	0.1	5.3	6.0

Acidity is total acidity; CEC is cation exchange capacity by ammonium saturation, OC is organic carbon

Table 4. Soil test characterization of grid sampling (n=100 observations).

Measure	pH	SOM(%)	Bray1-P (lbs/acre)
Mean	6.3	1.7	23
Standard Deviation	0.3	0.5	13
High Value	7.1	2.9	75
Low Value	5.5	0.7	3

	-----cmol/kg-----				
Measure	Total Acidity	Calcium	Magnesium	Potassium	CEC
Mean	0.47	7.8	0.9	0.14	9.3
Standard Deviation	0.65	1.1	0.2	0.06	1.4
High Value	5	10.7	1.3	0.26	14.0
Low Value	0	5.3	0.5	0.02	6.2

	-----mg/kg-----			
Measure	Iron	Manganese	Copper	Zinc
Mean	64	24	0.9	1.1
Standard Deviation	43	8	0.4	0.4
High Value	216	47	1.8	1.9
Low Value	14	9	0.2	0.2

depth. The exchangeable cations are dominated by calcium (Ca), especially in the near-surface soil horizons. The total acidity is highest in the Ap and lower Cambic horizons, with the deeper C3 and C4 horizons having the smallest total acidity values. The CEC is low (<12 cmol/kg) in the c horizons and medium (12–18 cmol/kg) in the near surface horizons, roughly corresponding with the clay and soil organic matter contents.

Distribution of Soil Test Values of the Ap horizons

Grid sampling was used to assess the soil variability across the crop science unit. The crop science unit was precision land graded in 2007, wherein the cut-sheet reveals areas where soil was removed (cut areas) and other areas (fill areas) where soil was deposited to create a level and gently sloping surface. Not surprisingly, cut areas generally have smaller soil organic matter contents, smaller Bray-1P levels, and smaller micronutrient availabilities, especially zinc.

Soil Moisture Evaluation during Irrigation

Soil scientists with USDA-NRCS field estimated the saturated hydraulic conductivity, volumetric water contents at (i) saturation, (ii) field capacity and (iii) permanent wilting point (Table 5). Water saturation is the experimentally determined soil water content when all of the soil pores are filled with water and typically saturation occurs immediately after a prolonged rainfall event. Within the variation of the soils in the study area, saturation volumetric water content ranges from 40 to 45%. The field capacity (field water capacity) is the soil water content approximately two to three days after a saturating rainfall and after free water drainage has become negligible. In the study area, the range in field water capacity is approximately 38–40%. Permanent wilting point is the largest soil water content when indicator plants growing in the soil wilt and fail to recover when placed in a humid chamber. The available water content is defined as the percentage of soil water between field capacity and the permanent wilting point (AW = FC-PWP). The water management allowed depletion (MAD) is the maximum allowed removal of water without appreciably reducing evapotranspiration rates; which in turn, reduce crop photosynthesis and yield potential. Typically, MAD is estimated to be approximately 60% of the available water content, which for the study are is approximately 22% (volumetric water basis).

Irrigation during the 2008 growing season was evaluated for corn production. A soil depth of 46 cm (18 inches) was selected after trenching alongside the corn rows to estimate the rooting depth, where approximately 80% of the total corn root surface area expression was visually estimated across the soil profile. Volumetric water contents ranged from four (22%) to six inches (33%) within the 18 inch rooting depth. These water contents were consistently above MAD, thus maintaining sufficient soil water contents to maintain optimum levels of canopy photosynthesis.

One key evaluation parameter necessary for the efficient operation of the subsurface controlled drainage/irrigation system is assessing the ability of irrigation/drainage water to horizontally migrate to maintain appropriate soil water contents between the tile lines. On 16 June 2009, soil moisture in the top 12 inches of soil reached MAD. Subsequent intense rainfall the following day re-established the volumetric water contents to saturation. Subsequent rainfall during the remainder of the growing season limited the usefulness of irrigation. Volumetric soil water contents were never substantially drier than field capacity for the remainder of the growing season (Figure 2). During drainage, the volumetric water contents on 9 July 2009 did not vary because of position with respect to the locations of the irrigation tiles. The subsurface controlled drainage irrigation system effectively removed excessive soil water and allowed timely field operations and normal to optimum plant growth and development.

Summary

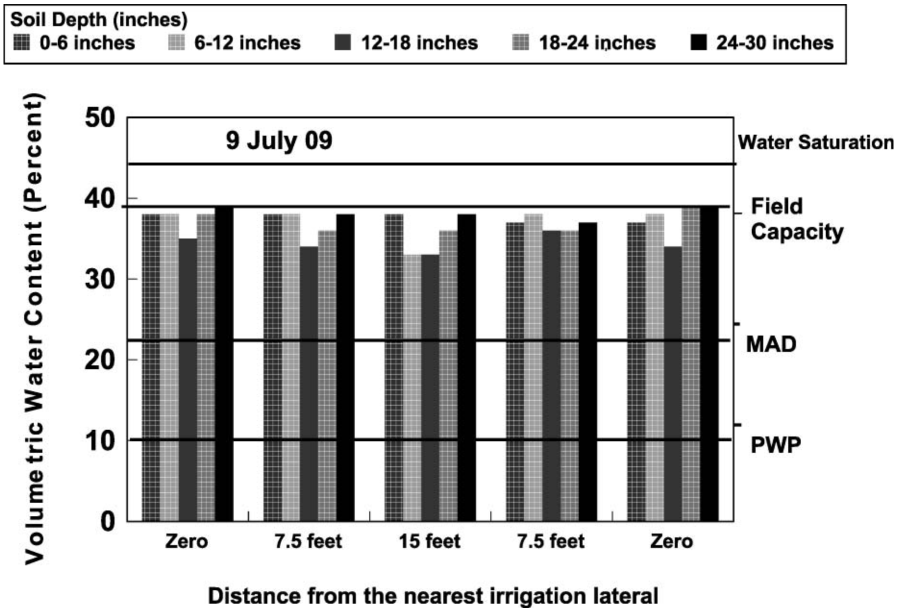
The soils of this study have sufficient reserves of plant essential elements to support plant growth and development.

Table 5. Saturated hydraulic conductivity (Ks) and diagnostic water estimates.

Series Cm Depth	cm/hr Ks	% Saturation	% Field Capacity(FC)	% PWP	% Available
Water					
Wakeland					
0–15	3.3	44	27	11	16
15–60	3.3	43	26	11	15
60–110	3.3	43	26	11	15
Wilbur					
0–15	3.3	44	30	15	15
15–60	3.3	45	25	9	16
60–110	3.3	45	25	9	16

PWP is permanent wilting point; Available water is FC-PWP

Figure 2. Mean volumetric soil water contents across a transect between irrigation laterals.



The major soil limitations include: (1) seasonal wetness and (2) low soil organic matter contents. Both conditions could limit available nitrogen because of insufficient mineralization and denitrification. Controlled drainage limits the effects of seasonal wetness, thereby promoting soil aeration, optimum root respiration and root growth. The designed controlled subsurface irrigation/drainage system operates efficiently to remove excessive soil water and provides sufficient irrigation water to maintain optimum crop yields.

References

Carter, M.R. 1993. Soil sampling and methods of analysis. Lewis Publ., Boca Raton, Fl.

"Design and Construction of Subsurface Drains in Humid Areas." ASAE.Standards. EP260. Dec. 4, 1996.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertilizers: An introduction to nutrient management. Prentiss Hall, Upper Saddle River, NJ.

Kanwar, R.S., J.L. Baker, and S. Muhktar. 1988. "Excessive Soil Water Effects at Various Stages of Development on the Growth and Yield of Corn." Transactions of the ASAE 31:133–141.

Moore, D.M., and R.C. Reynolds. 1989. X-ray diffraction and the identification and analysis of clay minerals. Oxford Univ. Press. NY.

Schwab, G.O., N.R. Fausey, and C.R. Weaver. 1975. Tile and Surface Drainage of Clay Soils: II. Corn, oats and soybean yields (1962–1972). Res. Bull. No. 1081. Ohio Agricultural Research and Development Center, Ohio State University, Wooster.

Schwab, G.O., N.R. Fausey, E.D. Desmond, and J.R. Holman. 1985. Tile and Surface Drainage of Clay Soils: IV. Hydrologic performance with field crops (1973–80) and V. Corn, oats and soybean yields (1973–80). Res. Bull. No. 1166. Ohio Agricultural Research and Development Center, Ohio State University, Wooster.

National Cooperative Soil Survey of Cape Girardeau County, Missouri. 1981. Festervand, D.F. (ed.). United States Department of Agriculture-Soil Conservation Service. U.S. Government Printing Office, Washington DC.

Soil Survey Division Staff. 1993. Soil survey manual. USDA Handb. 18. U.S. Gov. Print. Office. Washington, DC.

Soil Survey Division Staff. 2007. Official soil series descriptions [online]. Available at http://soils.usda.gov/technical/classification/osd/indent.html [verified June 2013]. USDA-NRCS.