SUBSURFACE DRAINAGE AND SUBIRRIGATION EFFECTS ON WATER QUALITY IN SOUTHEAST NORTH DAKOTA

X. Jia, T. M. DeSutter, Z. Lin, W. M. Schuh, D. D. Steele

ABSTRACT. *Rising water tables, increased soil salinity, and poor trafficability have prompted rapid expansion of subsurface drainage in the Red River Valley of the North in eastern North Dakota and northwestern Minnesota. A conventional subsurface drainage (CD) and subirrigation (SI) field study was conducted in southeast North Dakota from 2008 to 2010 to investigate drainage and subirrigation effects on water quality. Water samples were collected biweekly from a sump pump structure (used as the water inlet and outlet) and 16 observation wells within the field. Water quality variables included chloride (Cl^-), electrical conductivity (EC), total dissolved solids (TDS), sodium adsorption ratio (SAR), sodium (Na^+), orthophosphate (PO_4-P), ammonium (NH_4-N), nitrite and nitrate (NO_x-N), Kjeldahl nitrogen (TKN), and total nitrogen (TN). A three-factor partially nested design and a general linear model with random effects were employed to compare the effects of water management treatment, distance to drain, and well locations (soil heterogeneity) on water quality. The most significant water quality difference was found at the outlet structure, where a significant difference ($p < 0.001$) between the CD and SI water was found for all ten variables. The water quality of the drainage water was better than the subirrigation water from the aquifer, except for the NO_x-N, EC, and TDS concentrations. Well water Cl^- concentrations inside the field were significantly greater in SI compared with CD water; EC, TDS, SAR, and Na^+ were not. In contrast, EC, TDS, SAR, and Na^+ were significantly higher at two well locations, indicating that soil heterogeneity affected the water quality. Due to SI practice, a significant difference for Cl^-, SAR, and Na^+ was found between the locations closest to and farthest from the drains during the SI practice, which implies that the SI process may cause soil properties to change in the future. Overall, well locations significantly affected PO_4-P, NO_x-N, and TN, indicating that the soil physical and chemical properties affected the water quality, and these effects could overcome the difference due to different water treatments.*

Keywords. *Nutrient, Salinity, Subirrigation, Subsurface drainage, Water quality.*

In recent years, subsurface drainage has become popular in the Red River Valley (RRV) of eastern North Dakota and northwestern Minnesota following a wet-weather cycle since 1993. Rising water tables, increased soil salinity, and poor field trafficability during planting and harvest times have prompted the fast development of subsurface drainage in the RRV (Scherer and Jia, 2010). It is well known that highly soluble ions, such as nitrate and soluble salts, are higher in the subsurface drainage outflow compared to surface runoff from fields without a subsurface drainage system (Gilliam et al., 1999; Jayawardane et al., 2001), while orthophosphate is higher in surface drainage water (Eastman et al., 2010). To reduce the nitrate losses from subsurface drainage fields as well as to reduce subsurface drainage impact on surface water systems, controlled drainage can be used because it can maintain the water table at a depth favorable to crop growth using control structures (*ASABE Standards*, 2005; Skaggs et al., 2010). When the total volume of outflow from the subsurface drainage system is decreased due to controlled drainage practices, the chemicals leaving a field are also reduced according to a four-year study on 40 × 50 m plots conducted in southwest Sweden (Weestrom and Messing, 2007).

Subirrigation, a practice to apply water to fields for maintaining desired water table depths (*ASABE Standards*, 2005), is often combined with controlled drainage to provide a favorable moisture status for optimal crop production (Drury et al., 2008). The combination of controlled drainage and subirrigation can reduce nitrate losses by 46% to 63% compared with conventional subsurface drainage (Borin et al., 2001) and has been shown to increase corn and soybean yields by 19% and 49%, respectively (Fisher et al., 1999). However, the magnitude of crop yield increases may not always be the same and differs across crops and seasons (Elmi et al., 2002; Tan et al., 2002).

Soil and water quality within the field can be affected by subirrigation. Jayawardane et al. (2001) found that high salinity in the subirrigation water can cause secondary soil salinity over time. Fausey and Baker (2003) reported that

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subirrigation with high sodium concentration water caused changes in soil physical properties and decreased drainable porosity. After subirrigation has been applied in a field, water quality from the subsurface drainage outflow will be of mixed flow, and has been affected by the subirrigation water quality as well. Therefore, subirrigation water quality plays an important role in crop yield, drainage outflow, and the surface water system.

The water quality from the subsurface drainage outflow is affected by soil chemical properties. Madramootoo et al. (2007) stated that soil types and precipitation patterns were the primary factors influencing subsurface drainage effluent. Kuman et al. (1999) indicated large differences in nitrate concentration between simulated (with the Root Zone Water Quality Model) and measured results and attributed these differences to inadequate measurement of soil physical properties. Beauchemin et al. (2003) and Eastman et al. (2010) stated that phosphorus concentrations from subsurface drainage waters were significantly related to soil properties. Stutter et al. (2006) indicated that the outflow water quality from a large watershed was influenced by soil type, but the overall outflow chemistry of the water was controlled by a small tributary (3% of the total area) in the watershed, which was from a groundwater-dominated source. Even for two adjacent subsurface drainage pipes, when the soil is heterogeneous, the quantity and quality of the outflow can be different, so it is difficult to evaluate the differences in water quality, or specifically, the causes for variations in water quality (Vidon and Cuadra, 2010).

The relatively low slope (<2%) of the landscape of the RRV makes subirrigation an attractive tool for mid-season water delivery to plant roots. However, many questions remain unanswered regarding the usefulness of subirrigation in the RRV, especially since much of the aquifer water in this region contains Na^+, a known soil dispersant. In addition, the impacts of drainage and subirrigation on water quality have not been investigated in North Dakota. The objectives of this research were to compare the effects of water management treatment, distance to drain, and well locations (soil heterogeneity) on water quality.

Material and Methods

Experimental Site

The experimental site is located at Fairmount, Richland County, in southeast North Dakota, as described earlier by Jia et al. (2008), Pang (2011), and Rijal (2011). The geographic location of the field is 46° 00′ 45″ N and 96° 35′ 47″ W, and the elevation at the northeast corner of the field is 294 m above sea level. The climate in this region is typically continental, warm in the summer and cold in the winter. The annual average temperature is about 5.8°C, with the maximum temperature of 29°C in July and minimum temperature of -19°C in January. The total precipitation is about 557 mm, with 80% as rainfall and 20% as snowfall. The study site was cropped to corn (*Zea mays* L.) in 2008 and 2009 and soybean (*Glycine max* (L.) Merr.) in 2010. The crops were planted on April 19, May 17, and May 22 and were harvested on October 28, November 18, and September 30 in 2008, 2009, and 2010, respectively. A subsurface drainage system was installed in 2002 and has been operational since fall 2002. During 2008-2010, subirrigation was applied in the summer.

Field Layout

The total area of the experimental site is 22 ha. Eleven ha on the west side of the field had conventional drainage (CD) in spring and fall, and the other 11 ha (east side) had conventional drainage in spring and fall and combined CD plus subirrigation (SI) system in the summer (fig. 1). There

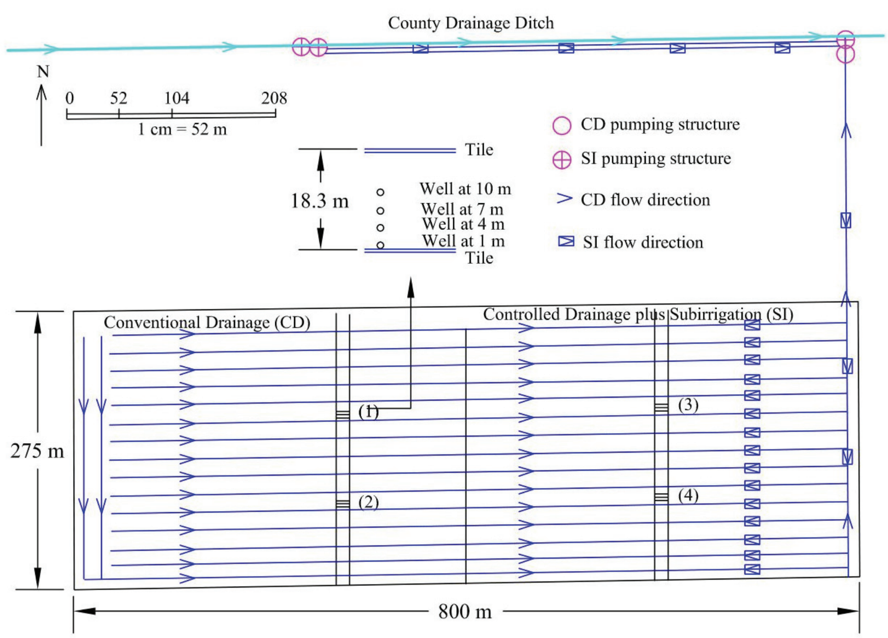

Figure 1. Field layout for the conventional drainage (CD) and subirrigation (SI) treatments, with sites 1 and 2 in the CD plot and sites 3 and 4 in the SI plot. The two vertical lines showed the locations of the permanent alleys.

was no isolation device installed between the two plots, and they shared the same drains. For a field drainage experiment that is conducted on a landowner's productive land, this setup was a shortcoming according to experimental design. During SI practice, the water level in the SI plot was controlled by the water level at the sump pump outlet structure for SI application. During SI application, the water level in the outlet structure was maintained between 1.13 and 1.44 m below the soil surface (the elevation at the sump pump was higher than the field), so that the SI water would stay in the SI plot and would not flow into the CD plot. A profile layout during the SI process across sites 2 and 4 is shown in figure 2. As stated by Rijal et al. (2012), the long length of the field (800 m), the high elevation difference between the two edges of the field (0.8 m), and careful SI application would have minimized the possibility for SI water to enter the CD plot. Normally, the SI application would take 3 days to bring the water level up to 1.13 m below the soil surface at the sump; after 3 days, the water table would again drop to 1.44 m below soil surface. Therefore, the water was intermittently pumped for the SI application. However, the actual water level at the observation wells showed less change (fig. 2) than expected.

The subsurface drainage system was operated as conventional drainage in early spring and late fall for draining excess water out of the field and turned off from late spring to early fall as controlled drainage, while the SI system was turned on in the summer to supply water into the field. The detailed schedule of the drainage and subirrigation practice in 2008 to 2010 is given in table 1.

A county drainage ditch is located about 275 m north of the experimental treatment plots, running from west to east, and drains into the Bois de Sioux River (a tributary of the Red River of the North) less than 2 km away. Two irrigation wells, located along the northwest sides of the field, were installed to a depth of 24 to 36 m in the Fairmount aquifer, with pumping capacity of 6.3×10^{-3} m^3 s^{-1} (100 gpm) for each pump. Two underground solid pipes were buried parallel to the county drainage ditch to deliver water from the irrigation wells to the SI structure at the northeast corner of the field, and water was then pumped to the CD structure for subirrigation. During spring and fall, when the drainage system was working, drainage water was pumped from the sump pump outlet structure to the surface ditch.

Table 1. Drainage and subirrigation during the experimental period.

Operation	2008 (month/day)	2009 (month/day)	2010 (month/day)
Conventional drainage	4/16 to 6/27	4/28 to 6/3	1/1 to 5/24
Controlled drainage	6/27 to 7/18	6/3 to 7/4	5/24 to 6/24
Subirrigation	7/18 to 8/8	7/4 to 9/5	6/24 to 8/27
Controlled drainage	8/8 to 9/5	9/5 to 10/1	8/27 to 9/10
Conventional drainage	9/5 to 11/3	10/1 to 12/31	9/10 to 12/31

The subsurface drainage system was installed in the fall of 2002 by a commercial drainage company. The system has a drain diameter of 10.2 cm, drain spacing of 18.3 m, and drain depth of 1.1 m at observation wells 1, 2, and 4 and depth of 1.34 m at observation well 3. The impermeable soil layer is greater than 2.1 m depth. The elevation of the field is higher in the west and north and lower in the east and south, but the highest elevation point is at the sump pump. The difference in elevation between the southwest and southeast corners of the experimental field is 0.74 m. With a 0.14% slope for the drainage system, also flowing from the west to the east sides of the field following the natural gradient of the field across the profile line (along the location of sites 2 to 4), the depth of the lateral in the west side of the field was estimated to be 0.6 m minimal (at 152 m from the west edge of the field); at the east

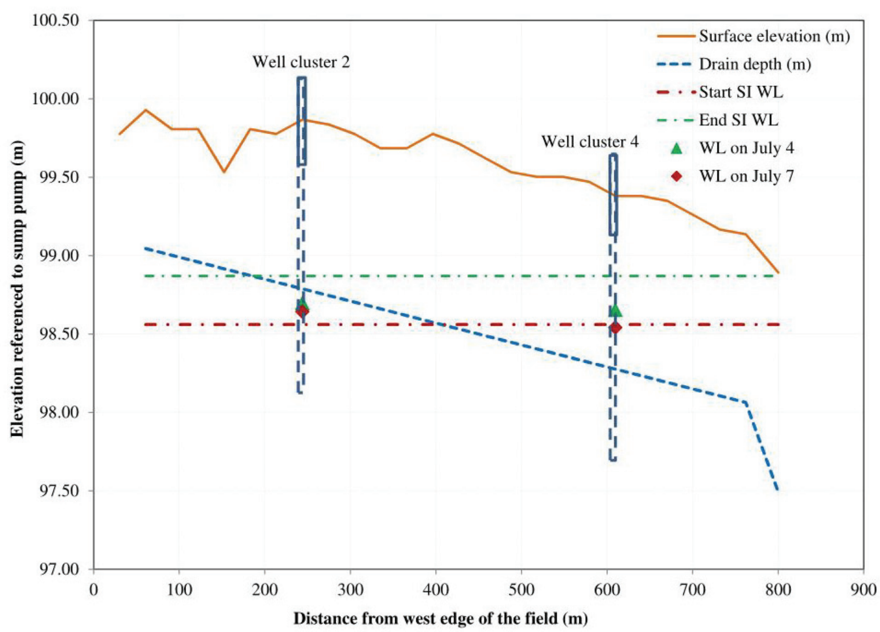

Figure 2. Field profile layout from the west to the east sides of the field during a subirrigation (SI) process on July 4-7, 2010. The red dashed line (lower line) shows the expected water level at the beginning of the SI process (Start SI WL), and the green dashed line (upper line) shows the expected water level at the end of the SI process (End SI WL). The measured water levels closest to the drain are marked by green triangles and red diamonds at well sites 2 and 4. The elevation at the sump pump is used as the reference point (100 m) for all other measurements.

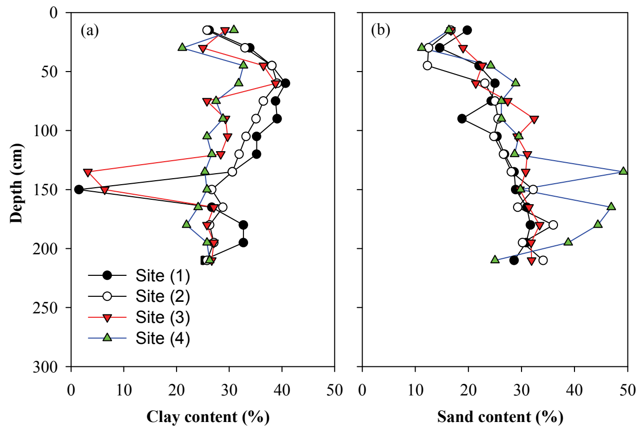

Figure 3. Soil (a) clay and (b) sand contents at the four testing sites. Sites 1 and 2 are in the conventional drainage plot, and sites 3 and 4 are in the combined controlled drainage and subirrigation plot.

edge of the field, the depth was 1.4 m (fig. 2). The size of the main drain was 38.1 cm. The sump is positioned 4.5 m below the soil surface and has a diameter of 1.98 m, and the drainage inlet is 2.2 m above the bottom of the sump pump (Scherer and Jia, 2010).

The soils in the CD plot were Clearwater-Reis silty clay (Clearwater soil series: fine, smectitic, frigid Typic Epiaquerts; Reis soil series: fine, smectitic, frigid Typic Calciaquerts), and soils in the SI plot were Antler-Mustinka silty clay loam (Antler soil series: fine-loamy, mixed, superactive, frigid Aeric Calciaquolls; Mustinka soil series: fine, smectitic, frigid Typic Argiaquolls) (USDA, 2012). Both soils have high clay contents, high water-holding capacities, low infiltration rates, and are poorly drained (USDA, 2012). Soil samples were collected at 15 cm intervals from the soil surface to 210 cm depth during fall 2007 at four sampling locations where wells were installed (fig. 1). Soil physical properties, including soil bulk density, particle size distribution, and saturated hydraulic conductivity (Jia et al., 2008), and chemical properties including electrical conductivity (EC) and pH were determined for every 15 cm soil layer across the field at the four sampling sites.

For both soil types, the clay and sand contents were similar for most layers. However, the clay content was near zero at 150 cm depth for sites 1 and 3 (fig. 3a) at the north side of the field in both the CD and SI plots. Below the 150 cm depth, the sand content for site 4 in the SI plot was about 50%, implying that the silt content was low at about 25%, compared to 55% silt content at 120 cm depth. Soil hydraulic conductivity increases with increase of sand percentage and decrease of clay percentage in the soil. The change in clay and sand content at 150 cm or below can have a direct impact on water movement downward or upward during the CD and SI applications.

INSTRUMENTATION

Water samples were collected from 16 observation wells, which were installed in two clusters of four wells in the two treatment plots (fig. 1). At each cluster location, four observation wells were installed to a depth of 2 m approximately 1, 4, 7, and 10 m from a drain. This design should give an approximate representation of water table distribution between two adjacent drains. Each observation well was installed using screened 5.1 cm diameter PVC pipe. The water table was measured automatically using HOBO water level transducers (model U20-001-01, Onset Computer Corp., Pocasset, Mass.) in each well and manually with a temperature level conductivity meter (Solinst, Georgetown, Ontario, Canada). The water table in each well was calculated from the absolute pressure and temperature recorded by the HOBO water level transducer and the barometric pressure from a nearby weather station every 30 min, and corrected with the manually measured reference water level during biweekly visits. The accuracy of the water level transducers is 0.3 cm, and they can operate between -20°C and 50°C. Each transducer was attached to and suspended from the well cap using a stainless steel cable. A laptop computer was used to download the data from the transducer via a coupler and an optical USB base station (COUPLER2-B, Onset Computer Corp., Pocasset, Mass.).

SAMPLING AND CHEMICAL ANALYSES

Water samples were collected biweekly from early spring to late fall. A PVC bailer was used to collect water samples from the observation wells and the sump. After water samples were collected, each field observation well was completely emptied to ensure that water disturbed during sampling was removed. Water samples were collected separately in two 500 mL and one 250 mL plastic bottles for different chemical analyses, as prescribed by the North Dakota Department of Health (NDDH), stored in coolers after sampling, and shipped the next day to the NDDH. Nitrate and nitrite-N (NO_x-N) were determined by EPA Method 353.2 and flow injection analysis (FIA), NH_4-N by EPA Method 350.1 and FIA, total N by Persulfate Method 4500-NorgD (APHA, 1995) and FIA, PO_4-P by Method 4500-P B.5 (APHA, 1998), Cl^- by EPA Method 300.0 and ion chromatography, total dissolved solids (TDS) by Method 1030 E (APHA, 2005), and conductivity (EC) by Conductivity Method 2510 (APHA, 1995). Total Kjeldahl nitrogen (TKN) was determined by EPA Method 351.2 using titration. Percent sodium was calculated as the ratio of (Na^+/23.1) to [(Na^+/23.1) + (K^+/39.1) + (total hardness/50)], and sodium adsorption ratio (SAR) was calculated as described by Gardiner (1994), where Na, Ca, and Mg were determined using inductively coupled plasma (ICP) spectrometry.

Soil samples were collected after harvest each year using a direct-push soil coring unit (9800E-87, Amity Tech., Fargo, N.D.), a 4.5 cm macro-corer, and plastic liners with caps in which the soil was stored until analysis. Soil samples were air-dried, ground to pass through a 2 mm sieve, and EC and pH were determined using 1:1 soil:deionized-water slurries using conductivity and pH probes, respectively (SensION 378, Hach Co., Loveland, Colo.).

Statistical Model for Analysis of Variance

Experimental Design

Samples of the well water were collected from the 16 observation wells at four well cluster locations in two treatment plots (CD vs. SI) during the three-year study period (2008, 2009, and 2010). As in all field studies, the real challenge is how to account for soil heterogeneity when comparing the effects of different treatments. In this study, a three-factor partially nested design was adopted (Neter et al., 1996). The three factors are water management treatment field (denoted as factor A), the distance from the sampling well to the drain (or distance-to-drain, denoted as factor B), and the well cluster location (denoted as factor C). Factor A has two levels: CD vs. SI, which considers the differences in water management treatment. Factor B has four levels: 1, 4, 7, and 10 m, which evaluates the water quality difference caused by the lateral water movement from or to the drain lines. The effects of site-specific soil properties on water quality are accounted for by including the random effect factor C, which consists of four different well cluster locations, with two in the CD plot and two in the SI plot. Note that factor C (well cluster location) is nested within factor A (water management treatment) since the two well cluster locations in the CD plot are different from the two in the SI plot. Also note that factors A and B are crossed, since each level of factor A appears with every level of factor B, and vice versa. Similarly, factors B and C are crossed. Factors A (treatment) and B (distance-to-drain) were considered to have fixed effects, while factor C (well cluster locations) effects were considered to be random because the locations of well clusters can be anywhere in the plots.

The response variables are ten water quality variables: five salt-related, including chloride (Cl^-), electrical conductivity (EC), total dissolved solids (TDS), sodium adsorption ratio (SAR), and sodium (Na^+), and five nutrient-related, including orthophosphate (PO_4-P), ammonium (NH_4-N), nitrite and nitrate (NO_x-N), Kjeldahl nitrogen (TKN), and total nitrogen (TN). We chose these variables because they are either the most commonly used water quality variables (i.e., NO_x-N, PO_4-P) or great concerns in our region (i.e., EC, SAR). The design is illustrated in table 2. It should be noted that, since each field observation well was completely emptied after water samples were collected each time, we assumed the biweekly water quality measurements were replicates, which are statistically independent of each other.

Random Effect Model

Since the effects of well cluster locations (i.e., soil types) are considered to be random, a general linear model with random effects (eq. 1) was employed to compare the effects of water management treatment, distance-to-drain, and soil type on well water quality. We also need to recognize that factor C is nested within factor A, and the AC and ABC interactions are to be excluded because factor C is nested within factor A. Finally, since factor C is nested within factor A, the BC interaction is nested within factor A. Therefore, the restricted mixed model is described as follows:

$$Y_{ijkm} = \mu_{\ldots} + \alpha_i + \beta_j + \gamma_{k(i)} + (\alpha\beta)_{ij} + (\beta\gamma)_{jk(i)} + \varepsilon_{ijkm} \quad (1)$$

where Y are (transformed) measurements of the response variable (i.e., each of the water quality variables), $\mu\ldots$ is an overall constant, α_i are the fixed water management treatment effects, β_i are the fixed distance-to-drain effects, $\gamma_{k(i)}$ are the random well cluster location (nested within water management treatment) effects, $(\alpha\beta)_{ij}$ are the fixed treatment × distance-to-drain interaction effects, $(\beta\gamma)_{jk(i)}$ are the random distance-to-drain × well cluster (nested within treatment) effects, and ε_{ijkm} are random error terms. All fixed effects are subject to the sum-to-zero restrictions. The subscript ranges are: i = 1, 2; j = 1, 2, 3, 4; k = 1, 2; and m = 1, 2, 3, …, n, where n is the number of replicates and is equal to the number of days when measurements of response variables were taken. We assume that $\gamma_{k(i)}$, $(\beta\gamma)_{jk(i)}$, and ε_{ijkm} are normally distributed with expectations of zero and with constant variances σ_γ^2, $\sigma_{\beta\gamma}^2$, and σ^2, and that the three groups of random variables are pairwise independent.

The statistical analysis of equation 1 was implemented using PROC GLM with RANDOM statement in SAS 9.2 (SAS Institute, Inc., Cary, N.C.). The ANOVA table for the random effect model (eq. 1) is shown in table 3. Firstly, it is worth noting that the fixed treatment × distance-to-drain interaction term, $(\alpha\beta)_{ij}$, was excluded from equation 1 when analyzing the main effects of factor A and factor B since the preliminary analysis of the model showed that the effects from this interaction term were insignificant for all water quality variables. Secondly, it should also be noted that the

Table 2. Balanced cross-nested experimental design for the conventional drained (CD) and subirrigated (SI) plots.

Distance to Drain	CD Plot (A1)		SI Plot (A2)	
(m)	Well Location 1 (C1)	Well Location 2 (C2)	Well Location 3 (C1)	Well Location 4 (C2)
1 (B1)	Replication 1	Replication 1	Replication 1	Replication 1
	Replication 2	Replication 2	Replication 2	Replication 2
	⋮	⋮	⋮	⋮
4 (B2)	Replication 1	Replication 1	Replication 1	Replication 1
	Replication 2	Replication 2	Replication 2	Replication 2
	⋮	⋮	⋮	⋮
7 (B3)	Replication 1	Replication 1	Replication 1	Replication 1
	Replication 2	Replication 2	Replication 2	Replication 2
	⋮	⋮	⋮	⋮
10 (B4)	Replication 1	Replication 1	Replication 1	Replication 1
	Replication 2	Replication 2	Replication 2	Replication 2
	⋮	⋮	⋮	⋮

Table 3. ANOVA table for random effect model (eq. 1).

Source of Variation	Degrees of Freedom	Mean Squares	Expected Mean Squares	F-Statistic
A	1	MSA	$8n\sum\alpha_i^2 + 4n\sigma_\gamma^2 + \sigma^2$	MSA/MSC(A)
B	3	MSB	$\frac{4}{3}n\sum\beta_j^2 + n\sigma_{\beta\gamma}^2 + \sigma^2$	MSB/MSBC(A)
C(A)	2	MSC(A)	$4n\sigma_\gamma^2 + \sigma^2$	MSC(A)/MSE
AB	3	MSAB	$\frac{2}{3}\sum\sum(\alpha\beta)_{ij}^2 + n\sigma_{\beta\gamma}^2 + \sigma^2$	MSAB/MSBC(A)
BC(A)	6	MSBC(A)	$n\sigma_{\beta\gamma}^2 + \sigma^2$	MSBC(A)/MSE
Error	$16(n\text{-}1)$[a]	MSE	σ^2	
Total	$16n\text{-}1$			

[a] n is the number of replicates for different response variables.

F statistic MSC(A)/MSE is meant to test the variation in measurements caused by the well cluster locations. If the variation caused by the well cluster locations is significant, then the effects from well cluster locations should be taken into account when comparing the water management treatment effect (i.e., CD vs. SI) on water quality. Hence, the denominator of the F statistics testing the main effect of factor A (treatment) is MSC(A) instead of MSE. The latter denotes the variation of pure measurement noise. The same principle applies to testing the effects of factor B (distance-to-drain) and of the AB interaction. The denominator of the F statistics for testing both effects is MSBC(A) instead of MSE. Thirdly, the Box-Cox transformation, along with Levene's test and visual inspection of residual plots, was employed to transform the salt-related variables to ensure homogeneity of variance for each response variable in equation 1 (Neter et al., 1996). No transformation was needed for nutrient-related measurements because Levene's test and the visual plots indicated that the nutrient-related measurements had constant variance before transformation. We used 0.1 as the level of significance for statistical tests.

Results and Discussion

Soil Properties

As indicated in the USDA-NRCS Web Soil Survey (USDA, 2012), the initial soil salinity levels were different for the Clearwater-Reis silty clay and Antler-Mustinka silty clay loam, while the largest differences were in the deeper soil layers. Large differences in EC and pH (0.41 to 4.69 dS m^{-1} and 7.68 to 8.16, respectively) were observed among the four sites and through the soil profiles (fig. 4). The soil EC level was lowest near the soil surface, possibly due to drainage and leaching, but increased with depth, indicating that the soil salinity in the parent materials was high. The increase in soil EC stabilized from 120 cm below the soil surface, where the drainage system was located, confirming that subsurface drainage had a positive impact on lowering the soil EC. Soil pH values behaved in the opposite way as soil EC, with large variations for the top soil layer (standard deviation 0.30) but consistent values below the drains (standard deviation 0.12). Site 1 showed a lower soil pH than the other three sites for soils below 90 cm depth.

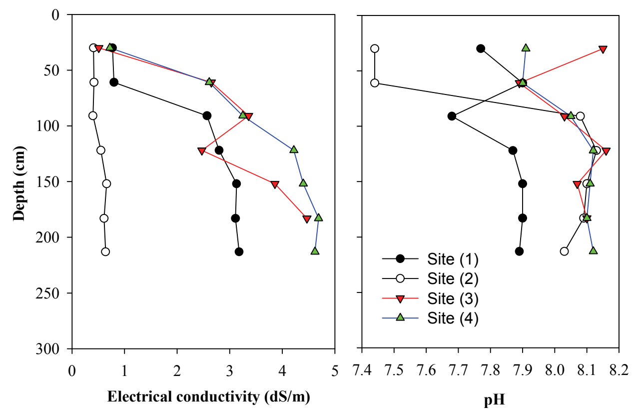

Figure 4. Variation in (a) soil electrical conductivity and (b) pH with soil depth at the four testing sites. Sites 1 and 2 are in the conventional drainage plot, and sites 3 and 4 are in the combined controlled drainage and subirrigation plot.

Water Levels

Daily total rainfall and average water levels of the four observation wells at the four well cluster locations are shown in figure 5 during the CD and SI applications in 2009 and 2010, while in 2008 the automatic water levels in the observation wells were not measured. Water level changes among the four observation wells in each of the well cluster locations were slightly different depending on the location and treatment (Fangmeier et al., 2006), and the detailed results are not listed in this water quality article. During spring drainage, the water levels were about the same. When the SI started in late June or early July, the water level started to differ between water management treatments, with the CD water level deeper than that in the SI plot due to the introduction of SI water. In late fall, when large rainfall events occurred, water levels rose in all wells. It was only through drainage for the late growing season that the water level could be reduced to ensure the crop being harvested on time, as the water level in the undrained field stayed near the soil surface (Rijal, 2011). At the end of the season, the water levels in the CD and SI plots both declined to similar levels where the drains are located because of water removal via the subsurface drainage system.

The water table at well cluster 4 was the shallowest among all locations. This was not surprising because, according to land survey, the land surface at location 4 is the lowest among all the wells. Using the sump pump location

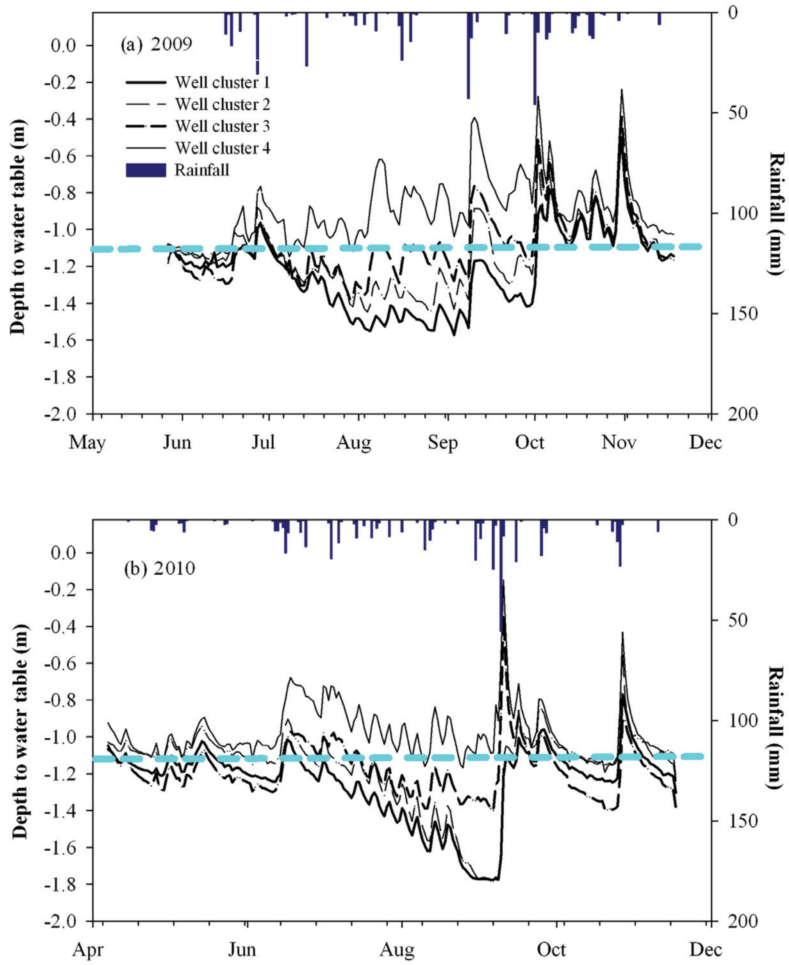

Figure 5. Daily rainfall and average depth to water table at the four well cluster locations in (a) 2009 and (b) 2010. Well clusters 1 and 2 represent the conventional drainage treatment. Well clusters 3 and 4 represent the controlled drainage and subirrigation treatment. The dashed horizontal lines represent the drain depth at well clusters 1, 2, and 4, while at well cluster 3, the drain depth is 1.34 m (not shown).

as the benchmark (the highest elevation), the elevations at well cluster locations 1 to 4 were 0.02, 0.13, 0.32, and 0.57 m below the benchmark, respectively, indicating that the shallow water table at this location might be due to the lower topography. The landowner indicated that before the subsurface drainage system was installed, the southeast corner of the field, where well cluster 4 was located, could not be planted in some years and had a lower crop production tendency due to the wet soil and poor drainage conditions. The lower ground level might also provide a chance for salt accumulation due to a shallower water level.

Irrigation Water Quality

The irrigation water was pumped into the drainage sump for subirrigation purposes from the Fairmount aquifer, a confined aquifer varying locally from about 3 to 6 m in thickness and located about 25 to 30 m below the soil surface. Based on data from the North Dakota State Water Commission well monitoring network, the water chemical composition is of the sodium bicarbonate type, as shown on the Piper plot for multiple water samples from six monitoring wells within 2 km of the irrigated field (fig. 6). The water quality is marginal for irrigation, having electrical conductivity between 1 and 2 dS m^{-1} (median about 1.1 dS m^{-1}) and sodium adsorption ratios ranging from about 4 to 6 (median 5; table 4).

Water Quality in Subsoil and Parent Material

The chemistry of natural pore water in the parent material sediments near the land surface but below the zone of crop influence and salt evaporative cycling at about 4.5 m below land surface is a calcium-sulfate type, distinctly different from that of the underlying aquifer (fig. 6, table 4). Before the introduction of irrigation water to the neighboring field (the experimental field), the electrical conductivity was higher in the parent materials, about 4.1 dS m^{-1} and the SAR was substantially low, at about 1.68.

Water Quality in Drainage and Irrigation Sump

The sump pump outlet structure was used either to hold drainage water from the field during the CD period or to add water to the field during the SI period. Similarly, the water samples collected at the sump pump outlet structure were either from the field through drainage or to the field through SI. Thus, the water quality at the sump pump outlet structure represents the water quality leaving or entering the field. For all ten water quality variables, a significant difference ($p < 0.001$) was found between the CD and SI

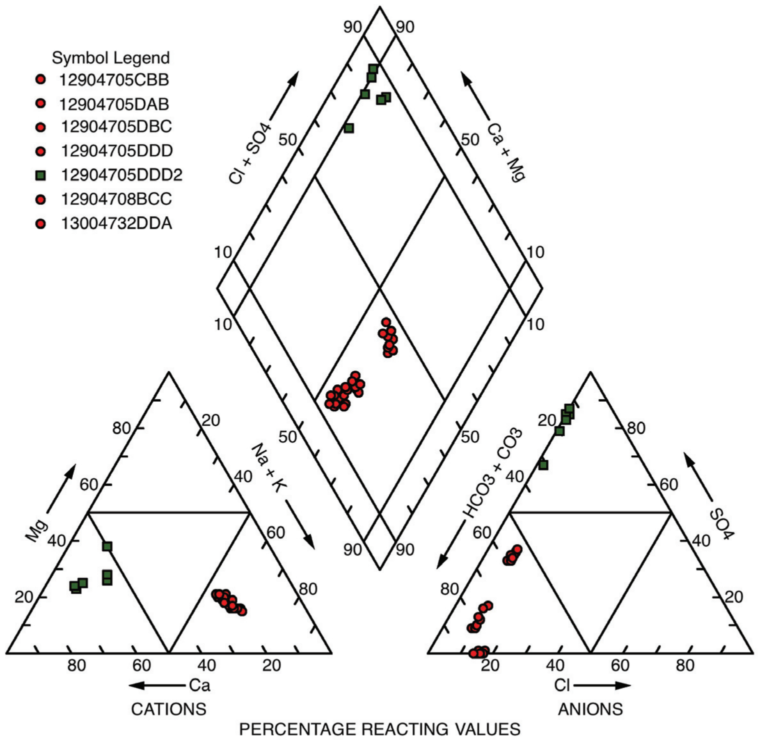

Figure 6. Piper plot showing the relative anion and cation distributions for six local observation wells in the Fairmount aquifer (red circles) and one observation well (green square) in parent material sediments at 4.5 m below land surface.

Table 4. Water quality variables for 28 water samples collected from six observation well sites within 2 km of the experiment field and for an initial water sample collected on September 5, 2007, from a screened well at 4.5 to 6 m below the land surface in fine sediments (till) located in a road ditch in the southeast corner of the experiment field.

Water Source	EC (dS m^{-1})	pH	Si (mg L^{-1})	Ca^{2+} (mg L^{-1})	Mg^{2+} (mg L^{-1})	K^+ (mg L^{-1})	Na^+ (mg L^{-1})	Fl^- (mg L^{-1})	HCO_3^- (mg L^{-1})	SO_4^{2-} (mg L^{-1})	Cl^- (mg L^{-1})	NO_x^--N (mg L^{-1})	TDS (mg L^{-1})	SAR
Fairmount aquifer														
Minimum	1.0	7.2	27	40	21	3	139	0.2	358	2	34	0.09	645	4.2
Maximum	1.8	8.0	31	94	57	5	302	0.5	1,090	205	128	0.35	1,180	6.4
Mean	1.2	7.8	29	59	32	4	190	0.4	623	107	59	0.13	803	5.0
Median	1.1	7.9	29	54	27	3	176	0.4	578	101	46	0.09	732	5.0
SE	0.05	0.04	0	3	2	0	8	0.01	47	14	6	0.01	35	0.1
Sediments at 4.5 m depth	4.1	7.4	-	344	101	11	138	0	251	1,380	22	0.31	1,600	1.7

water. Figure 7 shows the five salt-related water quality variables. The SI water contained higher Na^+ concentration and an SAR value of about 6, which is within the range of the aquifer water samples (table 4). Irrigation with high SAR water might cause soil dispersion and decrease soil drainable porosity (Fausey and Baker, 2003). The TDS and EC from the irrigation wells were much lower than the drainage water from the field, indicating that the soil was rich in soluble salts and the soil salinity was high. Comparing the water quality for the three years, SAR in the drainage water increased after SI application, implying that subirrigation with higher SAR water can increase the SAR in the field, and sequentially increase the SAR in the water that later drained out of the field. Although SAR values nearly doubled during the SI periods, they did not reach levels of concern. The EC from the drainage water was two times lower after SI was initiated in 2009 and 2010, compared with values in 2008, indicating some salt dilution of the well water due to water addition from the SI system or rainfall events, or reduction due to drainage. Addition of Na^+ through subirrigation water could be of concern if the drainage system further lowers the EC level and further leaches calcium and magnesium from the soil. Long-term periodic monitoring of water quality trends would be desirable to answer this question.

Figure 8 shows the five nutrient-related water quality variables for the three years at the sump pump outlet structure. Although the magnitude of the differences was smaller for the nutrient variables than for the salt-related variables, a clear difference was seen between the water quality variables during the CD and SI periods. PO_4-P, NH_4-N, and TKN were higher in the subirrigation water, while NO_x-N was higher in drainage water. Measured PO_4-P during the SI period was very similar to concentrations in the aquifer water, which varied from 0.33 to 1 mg L^{-1}, with a mean and median of 0.7 mg L^{-1} in water samples from five wells. The range of PO_4-P in the CD period water samples reflects background concentrations about an order of magnitude lower than the aquifer water (0.068 mg L^{-1}) in the subsoil sediments, possibly because of some periodic mixing with

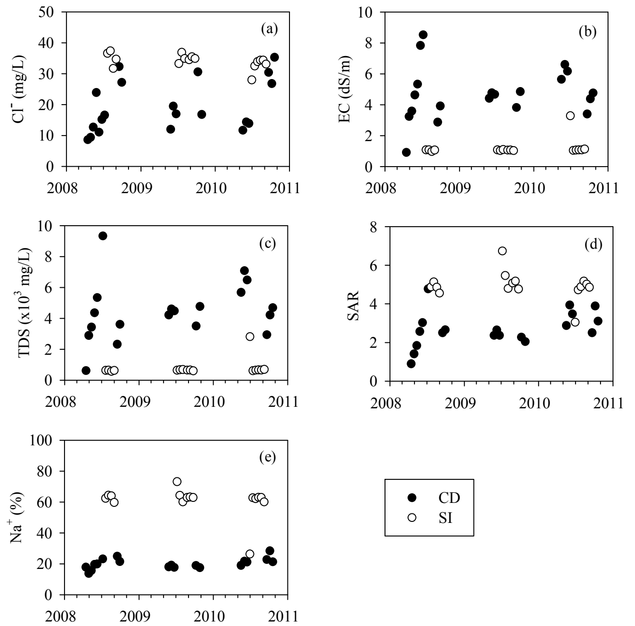

Figure 7. Comparison of salt-related variables at the sump pump structure for conventional drainage (CD) and subirrigation (SI): (a) chloride (Cl^-), (b) electrical conductivity (EC), (c) total dissolved solids (TDS), (d) sodium adsorption ratio (SAR), and (e) sodium (Na^+).

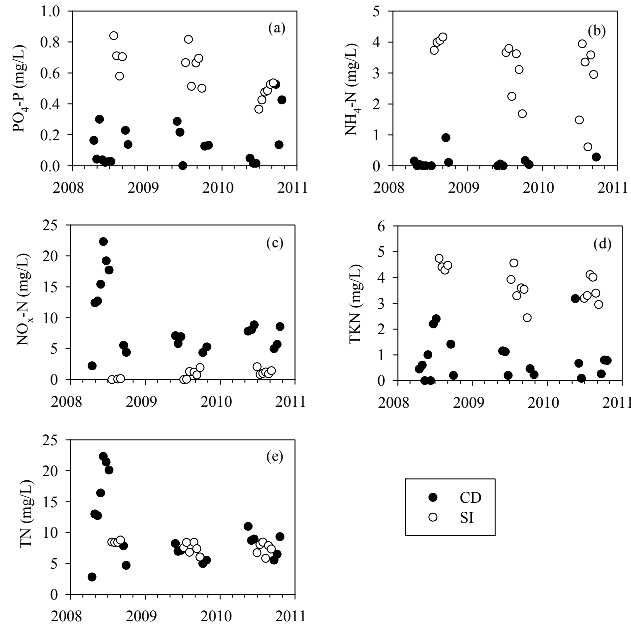

Figure 8. Comparison of nutrients variables at the outlet for controlled drainage (CD) and subirrigation (SI): (a) PO_4-P, (b) NH_4-N, (c) NO_x-N, (d) TKN, and (e) TN.

Table 5. Median, mean, and standard deviation (SD) at the outlet structure during conventional drainage (CD) and subirrigation (SI) period in all three years for ten water quality variables. The total number of samples varies from 16 to 20 for different variables and different water management treatments.[a]

		Cl^-	EC	TDS	SAR	Na^+	PO_4-P	NH_4-N	NO_x-N	TKN	TN
Median	CD	17	4.6	4360	2.6	20	0.1	0.0	7.4	0.9	8.5
	SI	34	1.1	645	4.9	63	0.6	3.6	0.9	3.8	8.0
Mean	CD	19	4.7	4450	2.7	20	0.1	0.1	9.3	0.9	10.2
	SI	34	1.2	777	5.0	61	0.6	3.1	0.9	3.8	7.7
SD	CD	8.4	1.71	1886	0.9	3.3	0.15	0.24	5.54	0.86	5.74
	SI	2.3	0.56	543	0.7	9.7	0.14	1.06	0.69	0.65	0.92

[a] Cl- = chloride (mg L^{-1}), EC = electrical conductivity (dS m^{-1}), TDS = total dissolved solids concentration (mg L^{-1}), SAR = sodium adsorption ratio (unitless), sodium (Na+, %), PO_4-P = orthophosphate concentration (mg L^{-1}), NH_4-N = ammonium concentration (mg L^{-1}), NO_x-N = nitrite and nitrate concentration (mg L^{-1}), TKN = total Kjeldahl nitrogen concentration (mg L^{-1}), and TN = total nitrogen (mg L^{-1}).

aquifer water or pore water containing fertilizer phosphate salts.

In 2008, TN was 2.65 times greater for CD water than for SI water, whereas TN was similar for CD and SI in 2009 and 2010. NO_x-N was the predominant form in which nitrogen was present. Nitrogen fertilizer was applied at a rate of 157 kg ha^{-1} during fall 2007, and higher NO_x-N was detected in the CD water from the field in spring 2008. In spring 2009, nitrogen fertilizer applications were applied in spring during planting. This change in application timing may have lowered the NO_x-N release rate to the drainage water and provided a better chance for crop use of nitrogen fertilizer. In 2010, no fertilizer was applied for soybean.

The results in table 5 are similar to the results in figures 7 and 8, showing that the CD and SI water qualities were significantly different from each other ($p < 0.001$). The mixing between the two sources of water can potentially benefit the crop because SI water with SAR 6 could be offset by high EC water in the soils, and soil dispersion was not found in soil samples after the three-year study. Because the concentration of NO_x-N was higher in the spring drainage than in the fall drainage, less drainage water in spring due to controlled drainage resulted in a smaller NO_x-N release to the surface water. In summary, the combined CD and SI application benefited the soil and water environment.

WATER QUALITY IN OBSERVATION WELLS

Brief descriptive statistics of the measurements for the ten water quality variables are provided in table 6. For most variables, there were 20 days or more of measurements available for analysis, except for NH_4-N and TKN, which had 13 and 16 days of measurement, respectively. In table 6, we can see that the standard deviations for all ten variables were close to or larger than the mean values. A large range exists for all ten variables, indicating that simple average values would not explain the water quality changes in temporal and spatial scales.

The measurement average for each water quality variable over the four observation wells at each sampling well cluster is presented in figures 9 and 10. In figure 9, well cluster 2 had the smallest averages, especially for EC, TDS, and SAR; well cluster 3 had the largest averages; and well clusters 1 and 4 had comparable averages for all the salt-related variables. The well cluster averages of the five salt-

Table 6. Descriptive statistics of the measurements of salt-related and nutrient-related water quality variables.

		Total No. of Measurements	Mean	SD	Median	Minimum	Maximum
Salt-related variables	Cl^- (mg L^{-1})	352	12.9	9.7	10.5	0.0	117.0
	EC (dS m^{-1})	352	5.9	4.8	4.4	0.4	23
	TDS (mg L^{-1})	352	6355	6100	4300	234	30600
	SAR (-)	352	3.48	3.22	2.29	0.33	15.10
	Na^+ (%)	352	19.4	9.1	19.1	2.6	38.1
Nutrient-related variables	PO_4-P (mg L^{-1})	320	0.215	0.263	0.171	0.0	2.81
	NH_4-N (mg L^{-1})	208	0.176	1.488	0.048	0.0	21.5
	NO_x-N (mg L^{-1})	384	18.5	11.8	16.6	0.15	81.5
	TKN (mg L^{-1})	256	1.53	1.97	1.00	0.0	17.9
	TN (mg L^{-1})	384	19.5	11.7	17.5	3.1	91.5

related variables were generally greater in the first year of the field study (2008) than in the next two years (2009 and 2010). This pattern was more obvious for well cluster 3, but less so for well cluster 2. Among all locations, well cluster 3 showed the highest values for all five variables, well cluster 1 in the CD plot followed as the second, instead of well cluster 4 in the SI plot. Well cluster 3 is the only location where pore water salt variables were strongly and consistently influenced by irrigation water chemistry. The early elevated Cl^- concentration is similar to aquifer water, and about double the concentration of subsoil water. However, the early elevated SAR, EC, and TDS values from well cluster 3 are much higher than the aquifer values. These were most likely caused by the mobilization of salts concentrated near the land surface by higher local water tables from subirrigation. Later EC and SAR values in 2009 and 2010 are very close to aquifer values, indicating that, after initial flush, aquifer water chemistry is locally dominant. While well clusters 1 and 3 are both located on the north side, the location of the wells in the field played an important role on salt distribution regardless of water management treatment. Specifically, the lower clay content and high silt content located at 150 cm depth just below the drains for site 1 and 3 may have contributed to the high salt levels for the two locations. We suspect that the two sites might have been interconnected, but this can only be confirmed through more intense soil samplings.

Figure 10 shows that the variation among the four well clusters for nutrient concentrations was less obvious than that for the salt-related variables (demonstrated in fig. 9), except that well cluster 3 tended to have greater averages than the other three well clusters for four nitrogen species in 2008. This is probably due to the fact that nitrogen fertilizer was applied in fall 2007 for the 2008 growing season but in spring for the 2009 season. Nangia et al. (2008) indicated that a 9% reduction in nitrate loss could be achieved in south-central Minnesota when changing the fertilizer application time from fall to spring using the calibrated Agri-

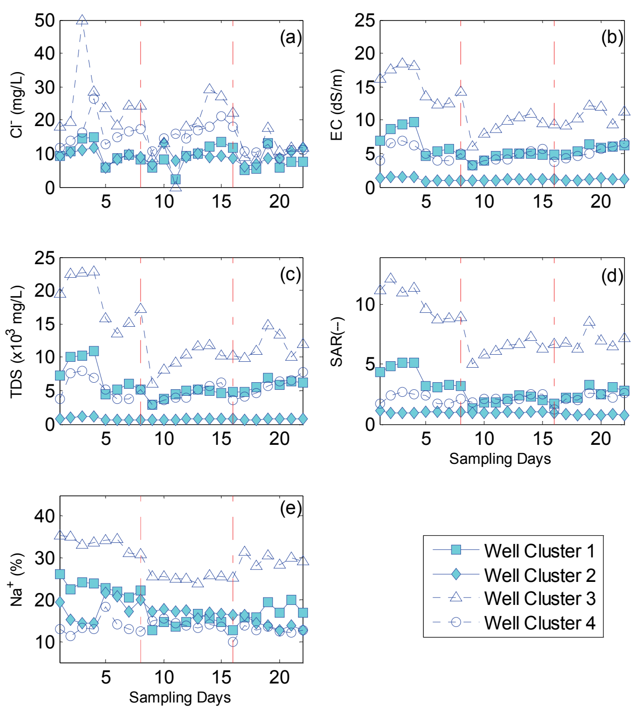

Figure 9. Comparisons of salt-related variables: (a) Cl-, (b) EC, (c) TDS, (d) SAR, and (e) Na+. Vertical dashed lines separate the sampling days into three years (2008, 2009, and 2010). Well clusters 1 and 2 are located in the conventional drainage (CD) plot, and well clusters 3 and 4 are located in the subirrigation (SI) plot.

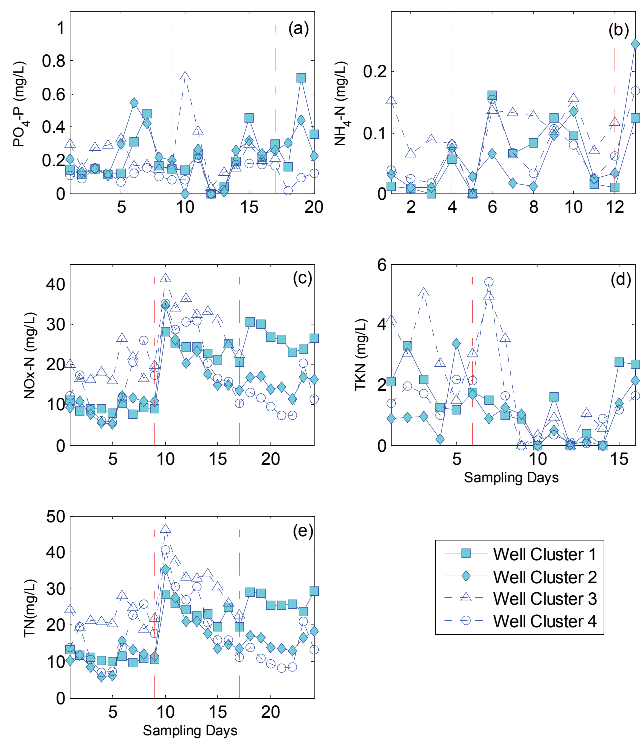

Figure 10. Comparisons of nutrients: (a) PO_4-P, (b) NH_4-N, (c) NO_x-N, (d) TKN, and (e) TN. Vertical dashed lines separate the sampling days into three years (2008, 2009, and 2010). Well clusters 1 and 2 are located in the conventional drainage (CD) plot, and well clusters 3 and 4 are located in the subirrigation (SI) plot.

cultural Drainage and Pesticide Transport (ADAPT) model, while we found a 50% reduction in NO_x-N concentration from spring 2008 to spring 2009. A single elevated PO_4-P measurement in well cluster 3 in 2009 approached the median PO_4-P for aquifer water. There was no apparently unifying temporal trend among the nutrients, either. Furthermore, the difference between the field averages (not shown) was less obvious than that for the salt-related variables. Comparing figures 10c and 10e shows that TN is mainly composed of NO_x-N.

ANALYSIS OF VARIANCE

STATISTICAL ANALYSIS FOR ENTIRE STUDY PERIOD

The levels of significance for testing treatment effects are 0.1. For salt-related variables, table 7 shows that Cl^- concentrations in the wells were significantly affected by SI operation (p = 0.012), which marked the difference between the two water management treatment plots, while the levels of the four other salt-related variables were not significantly affected (p > 0.1), especially Na^+ concentration (p = 0.934). It is also shown that the variation caused by the well cluster locations in the fields were not significant for Cl^- concentrations but were significant for the four other salt-related variables (referring to fig. 9 and the fourth row of table 7). This suggests that the Cl^- concentrations in soils were mainly affected by the Cl^- concentrations in the irrigation water, while the levels of EC, TDS, SAR, and Na^+ in the well water were largely influenced by the characteristics of the local soils.

Table 7 also shows that the variation caused by the interaction of distance-to-drain and well cluster location was significant for all salt-related variables (referring to the last row), which numerically contributed to the large p-values in testing the water management treatment and distance-to-drain interaction. Despite large $\sigma_{\beta\gamma}^2$ values, the F statistics for factor B (i.e., distance-to-drain) indicated significant main effects from distance-to-drain on the levels of Cl^-, SAR, and Na^+. However, the simultaneous multiple linear contrasts only showed the difference between the 1 m and 10 m distances to drain wells. In other words, the difference of Cl^-, SAR, and Na^+ only existed between the wells closest to (highest) and farthest from (lowest) the drains; there was no difference between wells adjacent to each other. The distance between two drains was 18.3 m, which was designed for drainage purposes but is too great (larger than desired) for SI purposes. Normally, SI systems require narrow spacing to achieve uniform water distribution between two drains, or particularly for locations closest to and farthest from the drain. Inadequate spacing was more evident in 2010 for shallow-rooted soybean than for deep-rooted corn. Non-uniform growth was observed for soybeans closest to and farthest from the drain. Higher Cl^-, SAR, and Na^+ content in the SI water only influenced the soil near the drain (or irrigation line), but the effect was very minimal in the middle between two drains.

Table 7. Analysis of variance for salt-related variables during the entire study period (p-values).

Source	Cl^-	EC	TDS	SAR	Na^+
Water management treatment	0.012	0.376	0.372	0.485	0.934
Distance-to-drain	0.034	0.138	0.158	0.068	0.037
Well location (field)	0.693	<0.001	<0.001	0.003	0.008
Treatment × distance-to-drain	0.541	0.184	0.182	0.251	0.205
Distance-to-drain × well cluster	0.075	<0.001	<0.001	<0.001	<0.001

Table 8. Analysis of variance for nutrient concentrations during the entire study period (p-values).

Source	PO_4-P	NH_4-N	NO_x-N	TKN	TN
Water management treatment	0.791	0.412	0.549	0.342	0.494
Distance-to-drain	0.359	0.510	0.823	0.756	0.782
Well location	0.005	0.382	0.094	0.108	0.052
Treatment × distance-to-drain	0.272	0.475	0.109	0.010	0.041
Distance-to-drain × well location	0.585	0.333	0.022	0.781	0.082

Water management treatment and distance-to-drain had no significant effects on nutrient concentration (table 8). Testing for variation caused by location of well clusters did not change this result. Significant differences in PO_4-P (p = 0.005), NO_x-N (p = 0.094), and TN (p = 0.052), but not NH_4-N and TKN levels, were linked to well location. Treatment and distance-to-drain p-values for TKN and TN are 0.010 and 0.041, respectively.

The PO_4-P concentration was higher in the SI water due to the relatively high P in the aquifer water used for irrigation (fig. 8). Further research is needed to investigate the sources and transport of P in the SI water. Following the SI path, higher P content was observed near the drain in the SI plot, while the water level was kept higher and longer (fig. 5).

STATISTICAL ANALYSIS FOR SEPARATED CD AND SI PERIODS

The water quality data in the 16 observation wells were analyzed using the same random effect statistical model for the separated CD and SI periods (tables 9 and 10). Separating the dataset into two periods did not change the results for water management treatment, distance-to-drain, and well location vs. analyzing the entire study period as a whole. Water management treatment and distance-to-drain effects on Cl^- concentration were mainly caused by SI practice (comparing tables 9 and 10), which confirmed the conjecture that the Cl^- concentrations in the well water were mainly affected by the Cl^- in the irrigation water. The Cl^- must be paired with Na^+ because both were higher in the irrigation water, but the Cl^- concentrations in both the CD and SI water were much below the 175 mg L^{-1} limit for North Dakota streams (NDDH, 2007).

It is also shown that the variation caused by the well cluster locations in the fields was significant for Cl^- during the SI period (table 10), which suggests that the wells in one location (i.e., presumably in the northern field) receive more SI water than the wells in the other location (i.e., in the southern field). This is true according to the SI path (fig. 1).

Table 9. Analysis of variance for salt-related variables during the conventional drained (CD) period (p-values).

Source	Cl^-	EC	TDS	SAR	Na^+
Water management treatment	0.153	0.372	0.372	0.497	0.927
Distance-to-drain	0.105	0.132	0.153	0.056	0.033
Well cluster	0.113	<0.001	<0.001	<0.001	0.006
Treatment × distance-to-drain	0.725	0.181	0.180	0.227	0.236
Distance-to-drain × well cluster	0.230	<0.001	<0.001	<0.001	<0.001

Table 10. Analysis of variance for salt-related variables during the subirrigation (SI) period (p-values).

Source	Cl^-	EC	TDS	SAR	Na^+
Water management treatment	0.094	0.379	0.373	0.492	0.941
Distance-to-drain	0.055	0.149	0.172	0.083	0.046
Well cluster	0.054	<0.001	<0.001	<0.001	0.012
Treatment × distance-to-drain	0.362	0.201	0.199	0.279	0.181
Distance-to-drain × well cluster	0.029	<0.001	<0.001	<0.001	<0.001

CONCLUSIONS

Significant differences were expected in water quality variables at the sump pump structure because the water sources were different for irrigation and drainage. We concluded that, according to nutrient parameters, the drainage water had better water quality than the SI water from the aquifer, except for nitrate N concentration. It is questionable that such differences would have a high impact in the field because of the many variables in a locale, such as soil properties, flow path, etc. Soil analysis revealed differences in properties for each soil layer at each location, but soil heterogeneity cannot be avoided in any situation. Therefore, in this study, we used a three-factor, partially nested design to ensure that effects of water management treatment, drainage, subirrigation, distance-to-drain, and well location (soil heterogeneity) were considered in the analysis of ten water quality variables.

Our results showed that, except for chloride, soil heterogeneity had the most effect on water quality variables. Chloride was most affected by irrigation water in the subirrigation applications. A higher sodium absorption ratio (SAR) in the subirrigation water did not cause significantly higher SAR in the two SI subplots. Rather, wells on the north side of the field had a higher SAR than the two well clusters on the south side of the field. This indicates that soil heterogeneity caused the difference in well water quality. Among all well cluster locations, site 3 in the SI plot, which was closest to the SI path, had the highest water quality variations for EC, TDS, SAR, Na^+, PO_4-P, NO_x-N, and TN, compared to the rest of the well clusters. This implies that the subirrigation practice changed the soil's physical and chemical properties, and will change well water quality and drainage water quality in the future if the SI practice continues.

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