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Research paper

Fate of water and nitrate using drainage water management on tile systems in east-central Illinois

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ABSTRACT

Drainage water management (DWM) is a potential edge-of-field technique that is being studied as a method to improve soil water management in agricultural fields, which may reduce nitrate losses to surface waters during the non-growing season. Inline water level control structures were installed on two adjacent tile systems draining a 34 ha field located in the Upper Salt Fork of the Vermillion River Watershed in central Illinois to evaluate DWM from 2011 through 2013. The overall objective of this study was to determine the effectiveness of DWM in reducing nitrate losses from fields in a corn and soybean production system in east-central Illinois, as well as to investigate the fate of the retained water. A paired watershed approach was used to determine the impact of DWM on tile flow and nitrate load compared to a control treatment or free drainage (FD) tile system. The entire 34 ha field was under a corn (Zea mays L.) and soybean (Glycine max L.) rotation with continuous no-till. During 2011 and 2012, DWM was able to greatly reduce tile flow compared to the FD tile system. However, based on runoff and nitrate yields from the entire field, there was no measureable reduction in nitrate loss and shallow ground-water wells showed little area of influence in the field (~2 ha). Water from the DWM tile system flowed laterally to the nearby FD tile system, increasing flow and nitrate loss from the FD system. In 2013, when both tiles were under DWM, water was retained and the water table level was increased in a larger area of the field (~6 ha). However, at the end of the experiment when the control stoplogs were lowered the retained water was discharged through the tiles lines with little apparent reduction (10%) in overall water and nitrate loss for the year. Measurements of tile and well nitrate concentrations suggested that nitrate was not denitrified in the shallow groundwater of the field during the three-year study. Nitrate losses were directly proportional to tile flow each year of the study. Retrofitting DWM on an existing tile system was found to have a limited water quality benefit.

1. Introduction

Intensive row crop agricultural production systems that contain subsurface drainage (tiles) are a major source of surface water nitrate loads in the Mississippi River basin (David et al., 2010) and fertilizer N and river discharge are key predictors of N export (Raymond et al., 2012). In central Illinois, riverine nitrate losses are often 20–30 kg N ha^{-1} yr^{-1}, and can be greater than 50 kg N ha^{-1} yr^{-1} during wet years (David et al., 1997, 2010; Royer et al., 2006; Gentry et al., 2009, 2014). At this latitude, tile drainage and nitrate transport to streams occurs during the late winter and spring season when no crops are present (Royer et al., 2004, 2006; David et al., 2010). Nitrate is thought to be a major contributing factor to the seasonal development of a hypoxic zone in the Gulf of Mexico (Rabalais et al., 2002). Some studies have found that stream nitrate loading is proportional to tile drainage flow (David et al., 2001; Adeuya et al., 2012) which is controlled by precipitation patterns (Gilliam et al., 1979; Royer et al., 2006; Drury et al., 2009; Cuadra and Vidon, 2011). One method that has been proposed to address this problem is drainage water management (DWM), an edge-of-field technique designed to reduce tile drainage and tile nitrate loads and possibly enhancing nutrient and water management for crop production (Lalonde et al., 1996; Strock et al., 2010).

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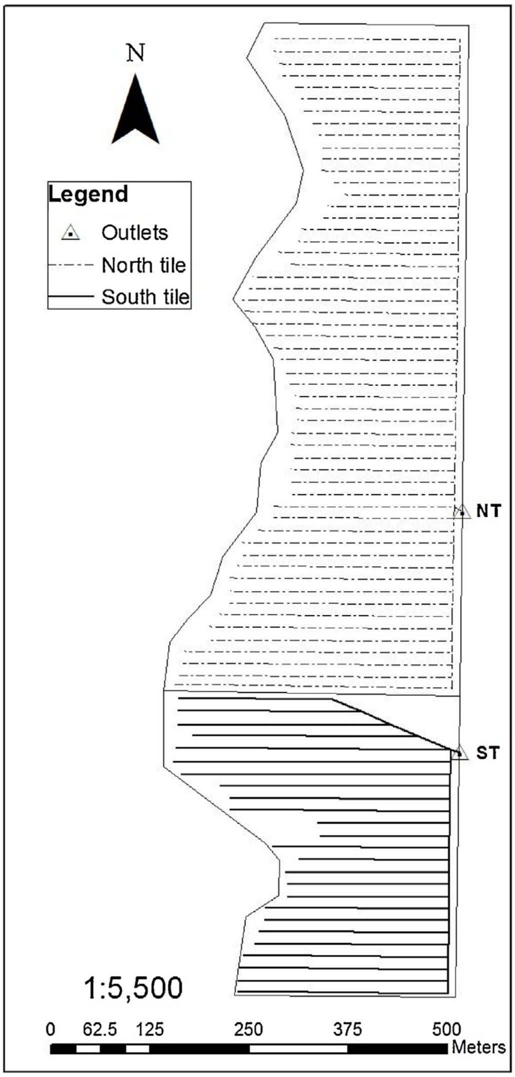

Fig. 1. Tile drainage design for the 11 ha south tile system (ST) and the 23 ha north tile system (NT).

The DWM method uses adjustable stoplogs within an inline water level control structure (Agri Drain Inc.) to manage the soil water table level in the field (Gilliam and Skaggs, 1986; Skaggs et al., 2012). In general, most published studies have used a paired watershed approach to evaluate the effectiveness of DWM compared to a conventional free drainage (FD) system. For this approach it is essential to include calibration periods to compare drainage from the paired systems during periods when both tiles are in free drainage mode (Gunn et al., 2016). Reviewing the literature to date, Skaggs et al. (2012) summarized DWM studies and found annual drain flow reductions that ranged from 16 to 89%, and nitrate load reductions by 18–82%, compared with FD systems. It has been hypothesized that applying DWM during the non-growing season will generate anaerobic conditions that may promote denitrification (Gilliam et al., 1979). However, most DWM studies do not indicate significant nitrate reduction via denitrification (Lalonde et al., 1996; Drury et al., 2009; Adeuya et al., 2012; Helmers et al., 2012; Jaynes, 2012), while others show only a small fraction of the missing nitrate likely to have been removed by denitrification (Mejia and Madramootoo, 1998; Woli et al., 2010; Smith and Kellman, 2011; Skaggs et al., 2012).

In some cases, DWM has been used to improve soil water status during the growing season; however, the main challenge was to keep the water table high enough for crop benefit, due to high evapotranspiration and low precipitation rates (Lalonde et al., 1996). Therefore some researchers combine DWM with subirrigation systems to maintain a stable water table during the growing season (Tan et al., 2002; Drury et al., 2009; Bonaiti and Borin, 2010). Anticipating when to raise and lower the stoplogs is a key factor for successful application of DWM during the growing season (Delbecq et al., 2012).

Several studies have suggested that there are three major sinks for the retained water during DWM: lateral seepage, deep percolation, and groundwater mixing (Wesstr&m et al., 2003; Skaggs et al., 2010; Cooke and Verma, 2012). Modeling work has estimated that by using DWM, lateral seepage increases by 15–17% (Wesstr&m et al., 2001; Thorp et al., 2008). Some researchers have installed plastic sheets to prevent the loss of water through lateral seepage (Wesstr&m et al., 2001; Helmers et al., 2012); however, this does not reflect the natural flow of shallow groundwater during typical field and weather conditions. In addition, Helmers et al. (2012) found the water table level increased rapidly after a rain event, but decreased after two days, instead of being retained in the soil. In a recent review article, Ross et al. (2016) also concludes that DWM is an effective conservation practice but identified the fate of water lost via other pathways (i.e. surface runoff and groundwater recharge) during DWM as an important knowledge gap. Furthermore, Cooke and Verma, (2012) acknowledged that because water left the DWM fields by pathways other than the tile outlet, the efficacy of the practice is likely less than reported. Collectively, these studies generate the question what is the fate of the retained tile water when DWM is applied and how does this effect efficacy?

The overall objective of this study was to use the paired watershed approach to determine the effectiveness of DWM compared to a FD tile system in reducing nitrate losses from fields in a no-till corn and soybean production system in east-central Illinois, as well as to investigate the fate of the retained water. Using the paired watershed approach we tested DWM on two adjacent field scale tiles (11 vs. 23 ha) during the winter-spring seasons of 2011, 2012 and 2013. We conducted our investigations into the fate of retained tile water using shallow well monitoring in 2012 and 2013.

2. Materials and methods

2.1. Site description

The study was conducted on a 34 ha field located in the Upper Salt Fork of the Vermillion River watershed located in east-central Illinois, USA. This area annually receives approximately 100 cm of precipitation (10 cm as snow) and average monthly temperatures range from −3.4 °C in January to 24.5 °C in July. Prairie soils in this area formed as loess or silty outwash over Wisconsinan till. The predominant soil types in this field were Drummer (fine-silty, mixed mesic Typic Haplaquoll) (64% of the field area), along with Flanagan and Raub (11 and 12% of the field area, respectively). These silty clay loam and silt loam soils are characterized for being poorly drained with high water-holding capacity and moderate permeability and are typical of the productive tile-drained Mollisols of east-central Illinois. The majority of the field topography is flat, with slopes less than 1%; however, steeper slopes (>2%) are found along the north-west side of the field. The field has been in a corn and soybean rotation under continuous no-till farming since 1985. Corn was grown in 2010 and 2012, whereas soybean was grown in 2011 and 2013. Prior to corn planting, diammonium phosphate (DAP 18-46-0) was applied during the winters of 2010 and 2012 at a rate of 224 kg ha^{-1}, which added 40 kg N ha^{-1}. In addition, starter fertilizer was applied in the form of liquid ammonium phosphate (10-34-0) at a rate of 11 kg N ha^{-1}. After planting, a side-dress of

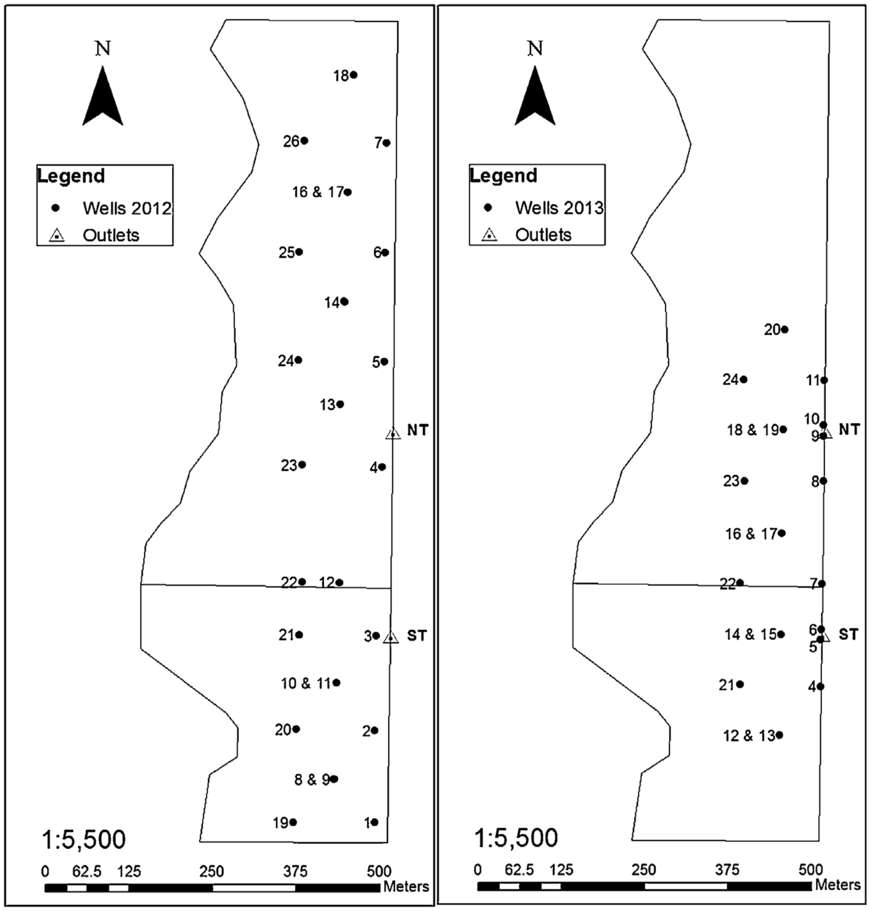

Fig. 2. Well and tile outlet locations during 2012 and 2013. Wells were positioned nearer to the water level control structures in 2013 to investigate lateral movement of retained shallow groundwater downgradient during periods of DWM.

anhydrous ammonia (NH_3) was applied at a rate of 180 kg N ha^{-1}. In total 230 kg N ha^{-1} were applied when corn was grown. No fertilizer N was applied to soybean.

2.2. Drainage design and management

The 34 ha field contained two adjacent subsurface tile drainage systems: South Tile (ST) and North Tile (NT), with areas of 10.9 and 23.1 ha, respectively (Fig. 1). Tiles consisted of perforated plastic and were previously installed (>5 years prior to our study). The field has a parallel tile drainage design, with lateral tiles of 15.2 cm in diameter with lengths from 165 to 348 m, spaced 15.1 m apart, and installed approximately 0.76 m deep with average slope of approximately 0.2%; slope increases with increasing topographic relief. Lateral tiles connected to a perpendicular main tile of 20 cm in diameter (approximately 10 m from the field edge and 1 m deep). Outlets mains (20 cm dia.) of each field were positioned in the lowest topographic areas on the field's border; however, NT was the lowest elevation across the field (approximately 12 cm lower than ST). An inline water level control structure (Agri Drain) was installed on the outlet of each tile system at the field's edge approximately 5 m from the center of a county road to the east of the field. The bottom of the structures are approximately 1.4 m below the soil surface as the two outlets continue under the road, ultimately leading east to a ditch approximately 100 m from ST and 300 m from NT. Adjustable stoplogs in each structure were used to increase and decrease the water level in the field (Strock et al., 2010; Cooke and Verma, 2012). Overall, three different water management approaches were tested during the three year study. Dates when stoplog settings were changed are listed in Table 1. In 2011, DWM was applied for 57 consecutive days on ST while NT was managed as FD. In 2012, DWM was applied on NT for 70 consecutive days, and ST was managed as FD. Finally, in 2013, stoplogs in both control structures were simultaneously raised and lowered during a 76 day period. During DWM, stoplogs were set as high as 106 cm (from the bottom of the control structure) for 5 days; however, concern for surface ponding prompted us to lower the stoplogs back

Table 1
Management of the stoplogs during the 3-year study, showing the height of the v-notch relative to the bottom of the water level control structures. DWM applied to ST from February 21 to April 18 in 2011, to NT from January 27 to April 5 in 2012, and to both ST and NT from February 1 to March 14 and again from March 21 to April 17 in 2013.

North Tile		South Tile	
Date	Height (cm)	Date	Height (cm)
		Dec. 29, 2010	36
Dec. 31, 2010	30		
		Feb. 21, 2011	79
		Feb. 22, 2011	96
Mar. 2, 2011	43	Mar. 2, 2011	93
		Apr. 18, 2011	32
Jan. 27, 2012	110		
Apr. 5, 2012	32		
Feb. 1, 2013	75	Feb. 1, 2013	75
Feb. 7, 2013	106	Feb. 7, 2013	106
Feb. 12, 2013	75	Feb. 12, 2013	75
Mar. 14, 2013	32	Mar. 14, 2013	32
Mar. 21, 2013	75	Mar. 21, 2013	75
Apr. 17, 2013	32	Apr. 17, 2013	32

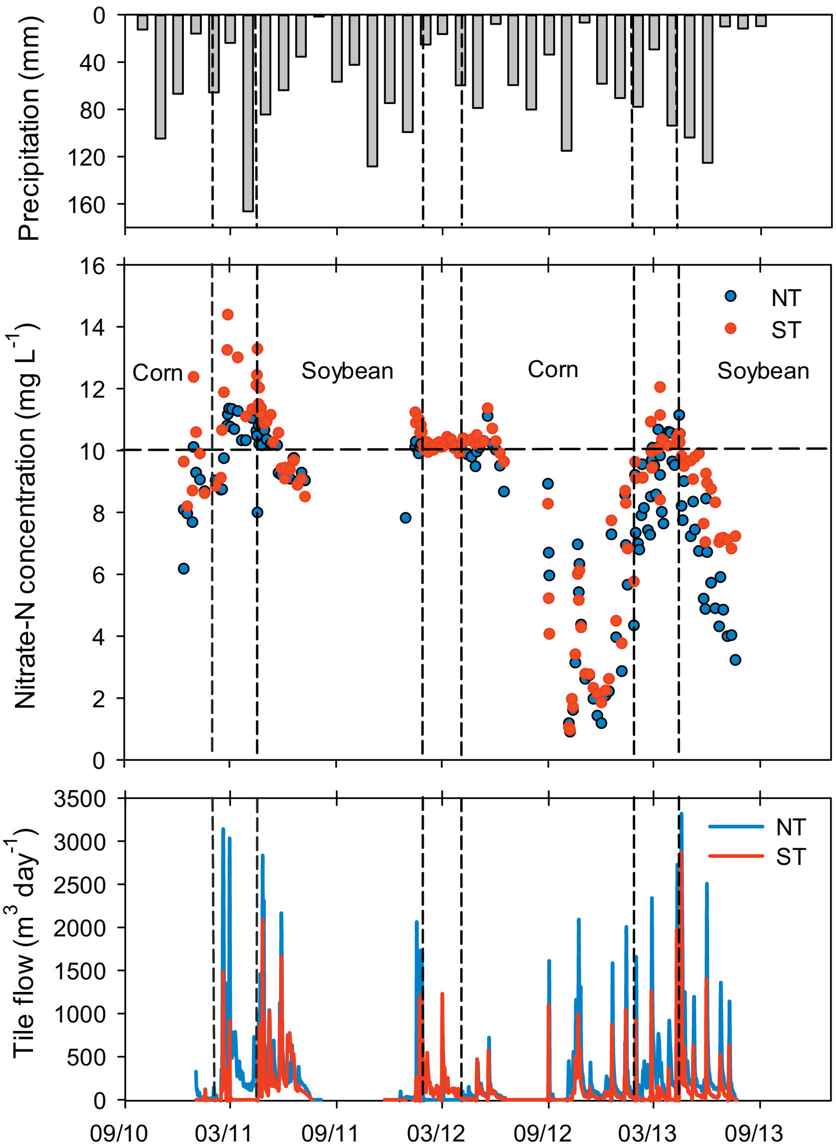

Fig. 3. Daily tile flow, nitrate concentration and monthly precipitation from 2010 to 2013. Vertical dashed lines represent the periods under drainage water management. Horizontal dashed line represents the US drinking water standard of 10 mg L^{-1}.

to 75 cm. After 42 days, stoplogs were lowered to 32 cm and water was allowed to drain out of the field for 7 days to see how quickly well water levels responded. Then stoplogs were again raised to 75 cm for 27 days until approximately 80 mm of rain forced us to release the water again to minimize flooding in the field.

2.3. Reference tile A

Having both tile systems simultaneously under DWM did not allow for an on-site FD reference tile to be used to determine the amount of tile water retained during the study period. We selected a reference tile from an evaluation of 5 concurrently monitored tiles on two nearby farms within this watershed. A linear regression model was developed using daily flow of ST and NT regressed against daily flow of each of the 5 tiles during periods of free drainage in 2011, 2012, and 2013 using SAS. One of the 5 tiles produced an R^2 of 0.77 with ST and an R^2 of 0.82 with NT. We chose this tile (Tile A) as our reference tile in 2013. Tile A was a patterned system with laterals 15.1 m apart, averaging 0.76 m depth, and draining 16.2 ha under a corn-soybean rotation located approximately 18 km to the north. Dominant soil types in the field of Tile A were Ashkum (poorly drained silty clay loam), Elliot (somewhat poorly drained silt loam), and Varna (moderately well drained silt loam). Corn production followed conventional tillage, while soybean production was no-till.

2.4. Flow measurements and water height settings

Each inline Agri Drain water level control structure was equipped with a 30.5 cm tall stoplog containing a 45° V-notch (17.8 cm from the bottom of the V to the top of the stoplog) and a pressure transducer and datalogger to record water depth at 30 min intervals. The bottom of the water level control structure was used as the reference elevation to compare and contrast with water table levels in the field (Figs. 5 and 11). In Agri Drain water level control structures, the bottom of the tile invert is 5 cm above the bottom of the structure. The height of the V-notch stoplog could be configured by various combinations of either 12.7 or 17.8 cm tall stoplogs placed under it. To convert water height to flow we used a v-notch discharge equation for Agri Drain water level control structures

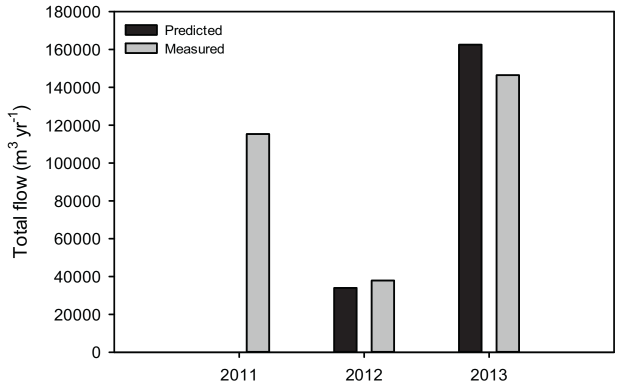

Fig. 4. Measured and predicted total annual tile flow from the 34 ha study site (NT plus ST) when compared to the reference tile (Tile A).

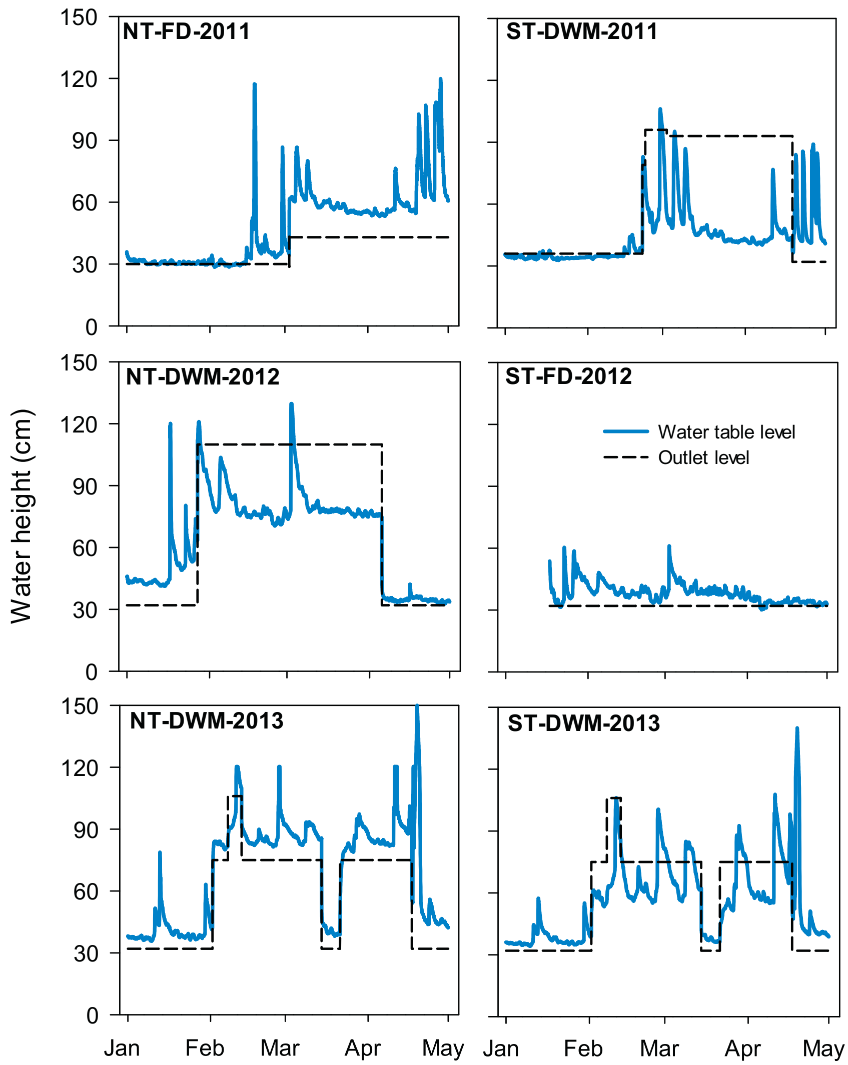

Fig. 5. Outlet stoplog settings (dashed lines) and water heights above the bottom of the water level control structures from the north and south tile systems (NT and ST) during drainage water management and free drainage periods.

developed under laboratory conditions by Dr. Richard Cooke in the Soil and Water Resources Engineering Laboratory at the University of Illinois.

The v-notch equation is:

$$Q = 1.4533H^{2.0464} \quad (1)$$

with additional equations for flow above crest:

$$Q = 0.020(l - 0.74H)H^{1.48} \text{ when } H \leq 0.27L \text{ or} \quad (21)$$

$$Q = 0.21LH^{1.37} \text{ when } H \geq 0.27L \quad (3)$$

where Q is discharge ($\mathrm{L\,s^{-1}}$), L is the width of the weir (cm) and H is the water level above the crest or weir (cm). The advantage of

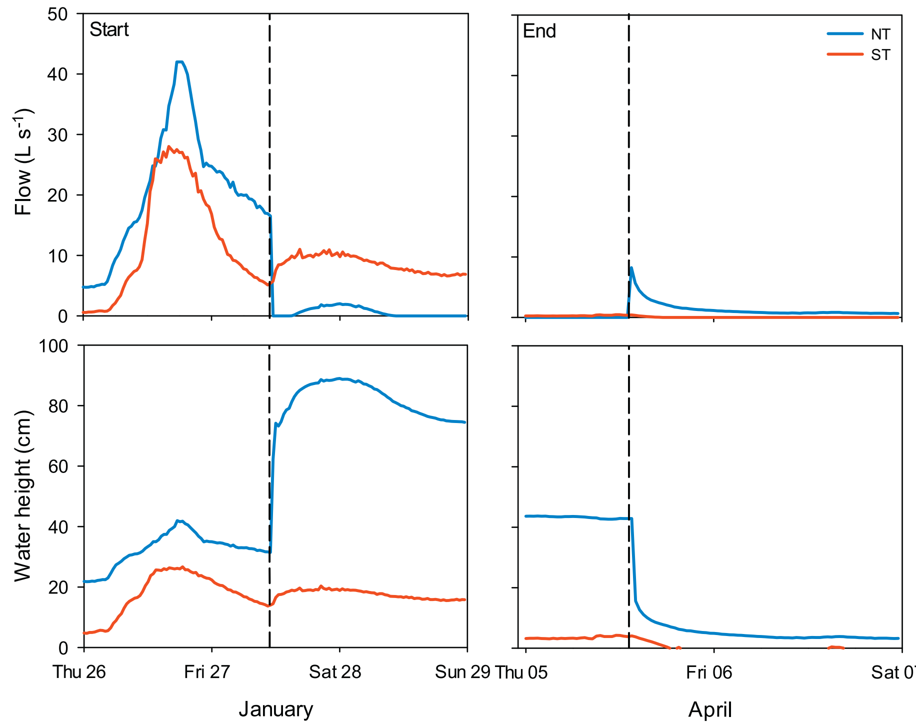

Fig. 6. Water heights above the bottom of the V-notch in each water level control structure and tile flow for NT and ST observed during the start and end of DWM application to NT in January and April of 2012. The dashed line represents the time when the stoplogs in NT structure were raised or lowered.

using these equations is that they can be adjusted for the specific conditions of each outlet and combined during high flow events.

2.5. Monitoring wells

Monitoring wells were used to estimate the area of influence that DWM had on the water table level and to measure nitrate concentrations in shallow groundwater across the field. The wells were made from PVC pipe 5.1 cm in diameter and 1.5 m in depth, with slot screens up to 10 cm below soil surface and open bottoms to allow the water to flow into the wells. A total of 22 and 21 shallow wells were installed across both tile systems in December of 2012 and 2013, respectively. Wells were positioned across the field at 0, 60 and 120 m lines and were monitored weekly during 2012 and 2013; however, the 0 m line of wells started 15 m from the field's edge in 2012, whereas the 0 m line of wells was positioned at the field's edge in 2013 (Fig. 2). The 0 m line was moved to the edge of the field in 2013 to investigate the potential flow of shallow groundwater around the water level control structures during periods of DWM. In addition, two 3 m deep wells (with slot screens from 1.5 to 3 m) were paired with two shallow wells in the 60 m line to examine the nitrate concentration in ground water below the tile drainage systems. The bottom of each structure was used as the reference elevation to indicate the change in height of water in wells during periods of DWM and FD (). Weekly well water levels were determined by hand using a Solinst water level reader. At the 60 m line across from the water level control structure in each field, wells 14 and 18 were instrumented with pressure transducers and dataloggers to record water level on a 30 min basis in 2013. Wells were removed before planting in both years.

2.6. Water sampling and analysis

Tile water samples were typically collected weekly or biweekly from December 2010 through November 2013, depending on precipitation and corresponding flow events. During some high flow periods samples were collected daily. A total of 280 water samples were collected for NT and ST during the study period. Tile water samples were collected in 500 ml non-acid washed plastic bottles, stored in a cooler and transported to the laboratory. Well water samples were collected weekly during the 2012 and 2013 study periods. Well water was pumped out before sampling. After at least an hour, a hand pump was used to collect the final water samples used for water quality analysis. Well water samples were collected in 125 ml non-acid washed plastic bottle, stored in a cooler and transported to the laboratory. All water samples were processed in the laboratory the same day or no later than 24 h after collection. Samples were filtered (Whatman® 0.45 μm mixed cellulose) and analyzed for nitrate using a Dionex DX-120 ion chromatography unit with detection limits of 0.1 mg N L^{-1}.

3. Results

3.1. Precipitation and tile flow

Total annual precipitation on a water year basis was 1080, 943 and 980 mm for 2011, 2012, and 2013, respectively. Monthly precipitation from January to June was 710, 369, and 634 mm for 2011, 2012, and 2013, respectively. An extreme drought developed during the summer of 2012, which ended with nearly 130 mm of precipitation in early September. Intensity and frequency of precipitation greatly influenced tile flow rates and total annual volumes (Fig. 3).

During 2011, DWM was applied to ST for 57 days during February and March. The annual flows from NT and ST were 82,249 m^3 and 33,099 m^3 (35.6 and 30.3 cm). Compared to the FD reference tile (NT), flow for ST was decreased. The flow ratio of NT to ST increased to 2.5:1 compared to the relationship of 2.1:1 when both tiles were under FD. Tile flow during the period of DWM was 1338 m^3 (1.2 cm) for ST and 25,960 m^3 (11.2 cm) for NT.

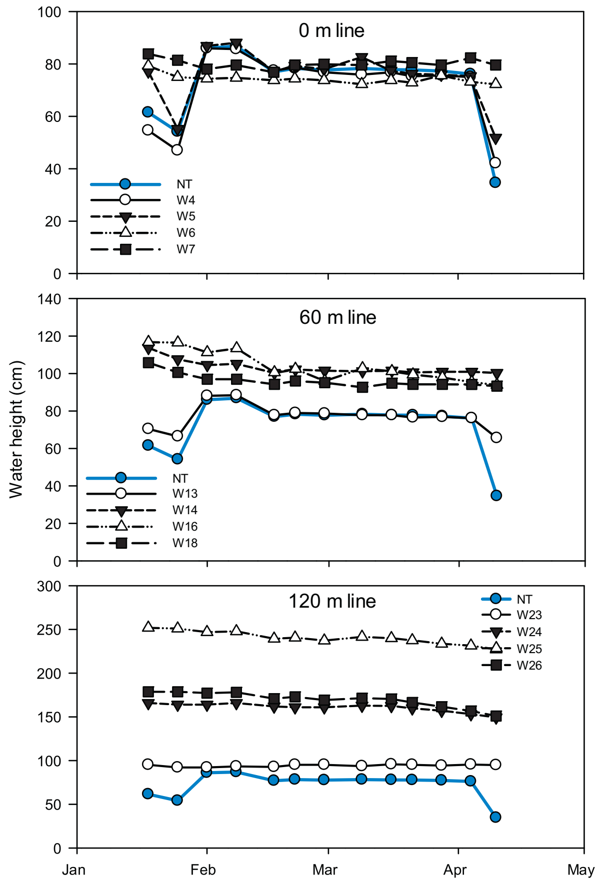

Fig. 7. Water heights in 2012 in the control structure and shallow wells located at 0, 60, and 120 m line for NT under DWM. DWM imparted January 27 to April 5. The water level is relative to the bottom of the control structure.

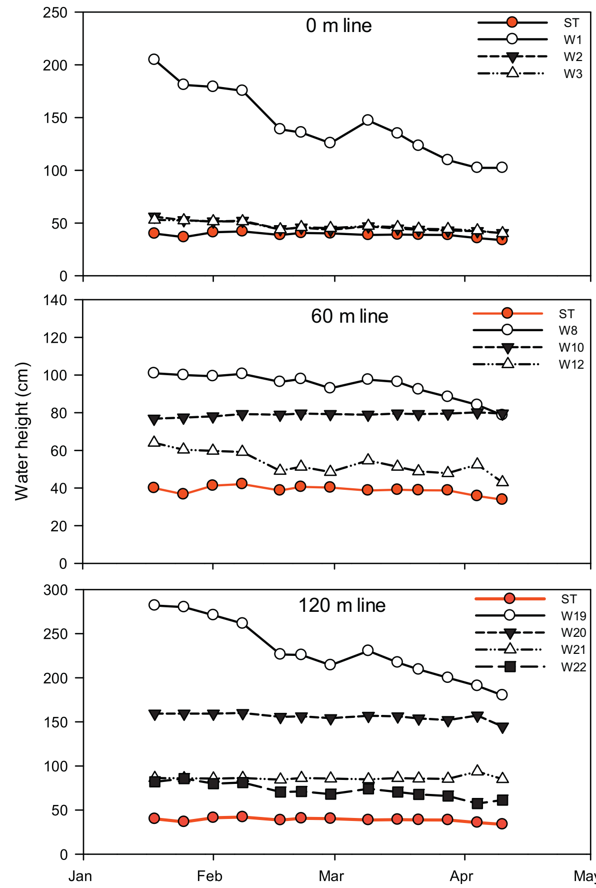

Fig. 8. Water heights in 2012 in the control structure and shallow wells located at 0, 60, and 120 m line for ST under FD. The water level is relative to the bottom of the control structure.

In 2012, DWM was applied to NT for 70 days from late January to early April. Precipitation amounts were much less in 2012 than in 2011 and total combined annual flow for NT and ST decreased by 66%. Compared to the FD reference tile (ST), flow for NT was greatly decreased by DWM and the flow ratio of NT to ST was 0.6:1. Total annual flow for NT was 17,472 m^3 (7.6 cm) while flow for ST was 27,428 m^3 (25.2 cm). Tile flow during the period of DWM was 1403 m^3 (0.6 cm) for NT and 13,170 m^3 (12.1 cm) for ST, but based on our comparison with reference Tile A, estimated total flow (NT + ST) from the entire 34 ha field was not decreased during DWM (Fig. 4).

In 2013, DWM was applied to both NT and ST for a total of 76 days. During periods of DWM, reference Tile A was used to estimate the volume of retained water. The total annual flow from NT and ST was 103,237 and 43,217 m^3, respectively; representing 44.8 and 39.6 cm of subsurface flow for each tile. With both tile systems in DWM, ST had proportionally less flow than NT and the NT to ST ratio increased to 2.4:1. The total combined annual flow of NT and ST was 146,454 m^3 (43.1 cm) and compared with the reference Tile A, we estimated a 10% reduction in flow for the 34 ha field (Fig. 4).

). We did not find an increase in the water height in any wells located in the field with the ST system in 2012 (Fig. 8

3.2. Water level in control structures

In 2011 when DWM was applied to ST, we were not able to maintain an elevated water level in the water level control structure (and presumably the field), even after receiving 33 mm of precipitation in three consecutive rain events in early March (Fig. 5). In 2012, when DWM was applied to NT, an elevated water level was maintained 75 cm from the bottom of the structure (65 cm below the soil surface), and water was retained in the field during the entire DWM period. However, when re-examining flow data immediately before and after the time when DWM was imparted on NT in 2012, we found tile flow began to increase in ST beginning 6 h after raising the stoplogs in NT (Fig. 6). Furthermore, immediately following the removal of stoplogs in NT to end the period of DWM in April, we observed a decrease in flow in the ST system and flow soon ceased (Fig. 6).

In 2013, stoplogs in both water level control structures were raised and lowered and then raised and lowered again for a second period of DWM (Fig. 5). The water level in the control structure was elevated and maintained throughout both periods of DWM. When the stoplog setting was raised to 106 cm above the bottom of the structure during the first period of DWM in February, we observed interflow and ponding of water around the control structure of NT after a heavy rain event. On Feb. 12, we removed stoplogs to decrease the water level by 31 cm (75 cm from the bottom the structure) to lower the water table (Table 1; Figs. 5 and 11). On March 14, stoplogs were lowered to 32 cm and tile water quickly flowed out of the fields and reached a stable base flow within 72 h (Fig. 5). On March 21, stoplogs were again set to 75 cm and water began to increase in the structure and the wells (Fig. 11). However, the second period of DWM that year was brought to an end after 80 mm of rainfall occurred between April 10 and April 16, and when more rainfall was forecast, the stoplogs were removed to decrease the water level by 43 cm on April 17. The field received another 50 mm of rainfall on April 18, which created extreme ponding in

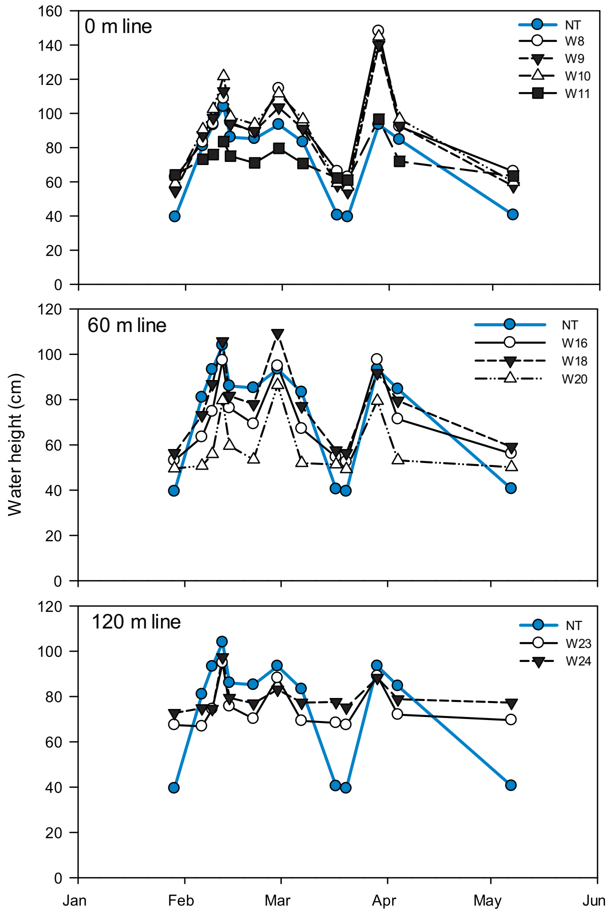

Fig. 9. Water heights in 2013 in the control structure and shallow wells located at 0, 60, and 120 m line for NT under DWM. DWM imparted February 1 to March 14 and March 21 to April 17. The water level is relative to the bottom of the control structure.

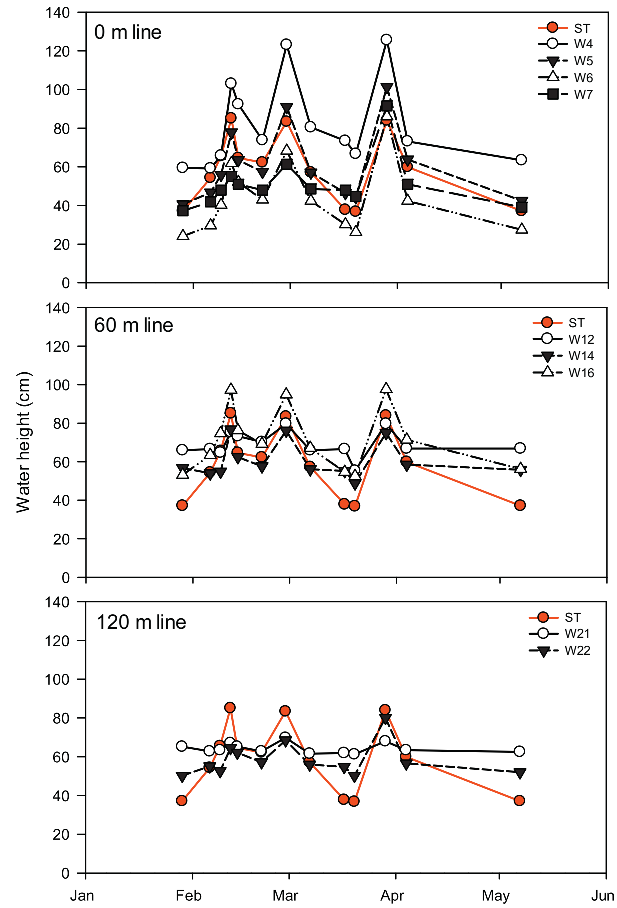

Fig. 10. Water heights in 2013 in the control structure and shallow wells located at 0, 60, and 120 m line for ST under DWM. DWM imparted February 1 to March 14 and March 21 to April 17. The water level is relative to the bottom of the control structure.

this field, completely submerging the water level control structures and producing flow over the roadway.

3.3. Well water levels

In 2012, DWM on NT increased the water level in two wells (W4 and W5) in the 0 m line and one well (W13) in the 60 m line; while no increase in well water height was observed in the 120 m line (Fig. 7). Water heights were relatively constant within most wells in ST (W1 and W19 were exceptions) (Figs. 7 and 8).

In 2013, when using DWM on both NT and ST, the water level in all wells was influenced by stoplog settings; however, wells 20, 21, 22, 23 and 24 showed minimal response (Figs. 9 and 10). Well water heights paralleled the water height in the water level control structures with the greatest change of water height in wells in the 0 m line for both drainage systems. Several rain events produced well water heights that were within 30 cm of the soil surface in the 0 m line. Water levels in wells 5, 6, 9, and 10, located 15 m on either side of the water level control structures had similar water heights as in each respective control structure (Figs. 9 and 10). At the 60 m line closest to the control structure in each field, continuous measurements of water levels in wells 14 and 18 showed a positive relationship to the increase and decrease of the water level in the control structures, responding quickly to rain events (Fig. 11). The release of retained drainage water in March showed how quickly water can drain out of the field as indicated by an immediate drop in water height in well 18.

Several of the deep wells located at the 60 m line installed in 2012 and 2013 had water levels greater (2–4 cm) than their paired shallow well. We observed that these wells were installed through a blue-gray silt layer found at a depth of approximately 2.5 m. The blue-gray silt layer may have acted as an impermeable barrier which separated deep water from shallow ground water. Therefore, we assumed that the deep wells were intercepting a different source of groundwater than the shallow wells.

3.4. Tile nitrate concentrations and loads

Both tiles had similar patterns of nitrate concentration for a given year during the three year study. Across both drainage systems, tile nitrate concentrations ranged from a low of 0.9 mg N L^{-1} in October of 2012 for NT to a high of 14.4 mg N L^{-1} in March of 2011 for ST (Fig. 3). In 2011 and again in 2013, nitrate concentrations began relatively low, increased during the winter and spring, and then decreased in late spring and early summer. In contrast, tile nitrate concentrations changed little during the entire drainage season of 2012. Interestingly, following the extremely dry summer of 2012, the remnants of a hurricane (Isaac) reached central Illinois, breaking the drought, and producing tile flow throughout the fall. Tile nitrate concentrations were unusually low during the fall of 2012 in both tiles.

Annual nitrate yields in 2011 for NT (FD) and ST (DWM) were 34.8 and 31.9 kg N ha^{-1}, respectively. Flow weighted mean nitrate-N concentrations were 9.8 and 10.5 mg L^{-1} for NT and ST. In 2012, nitrate yields for NT (DWM) and ST (FD) were 7.6 and 25.8 kg N ha^{-1}

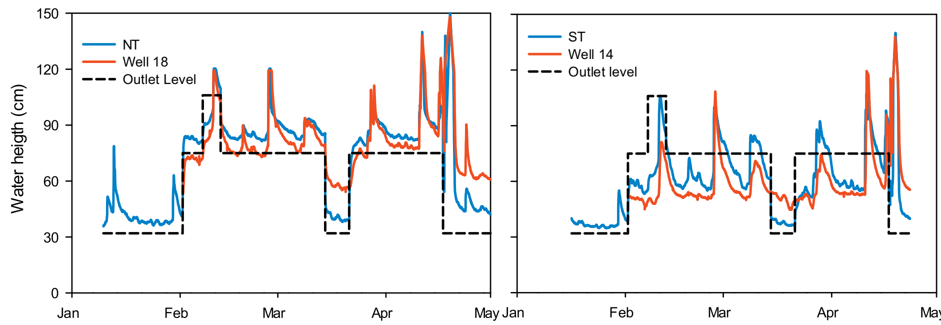

Fig. 11. Water heights in the water level control structures and two wells located at the 60 m line during 2013. The water level is relative to the bottom of the water level control structure.

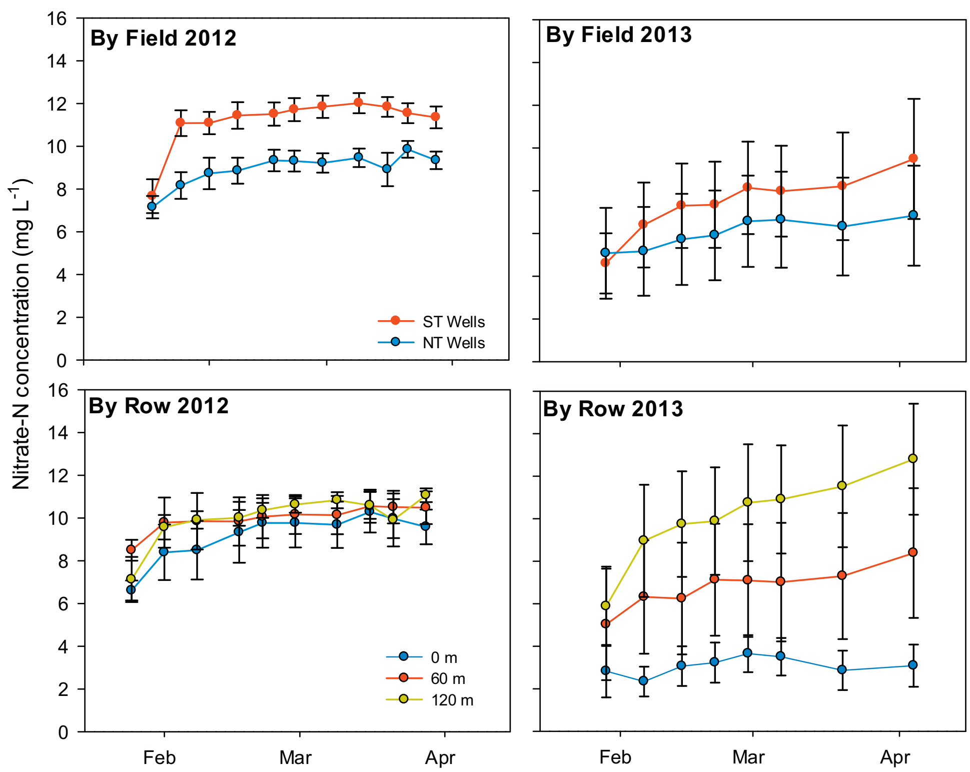

Fig. 12. Average nitrate concentrations with standard errors in wells by tile system during 2012 and 2013 (top figures). Average well nitrate concentrations at 0, 60, 120 m lines across the entire field (NT plus ST) during 2012 and 2013 (bottom figures).

and flow weighted mean nitrate-N concentrations were 10.1 and 10.4 mg L^{-1}. Finally in 2013, when both tiles were simultaneously under DWM for part of the year, the annual nitrate yields were 31.8 and 31.6 kg N ha^{-1} for NT and ST. Flow weighted mean nitrate-N concentrations were much lower in 2013 than in the previous two years (7.1 and 7.9 mg L^{-1} for NT and ST, respectively). Overall, flow weighted mean nitrate-N concentrations were lower for NT than ST each year with a three year flow weighted mean concentration for each tile of 8.1 and 9.0 mg L^{-1}.

3.5. Well nitrate concentrations

In 2012, shallow well nitrate-N concentrations across both tile drainage systems ranged from 2.8 to 14.7 mg N L^{-1}, with an average nitrate-N concentration of 9.5 mg N L^{-1} (Fig. 12). In 2012, the average well nitrate-N concentration was lower in the NT field compared to the ST field (9.1 and 11.6 mg N L^{-1}, respectively). The deep wells showed more variability in their nitrate concentrations with concentrations ranging from 0.1 to 12.7 mg N L^{-1}. Overall, however, nitrate concentrations in the deep wells decreased throughout the study period each year (data not shown).

In 2013, the shallow well nitrate concentrations were more variable than in 2012 and ranged from 0.1 to 21.8 mg N L^{-1}, with an average concentration across both drainage systems of 6.8 mg L^{-1}. Similar to 2012, the average well nitrate-N concentration in 2013 was lower in NT than in ST (6.0 and 7.4 mg N L^{-1}, respectively). The wells located in the 0 m line in 2013 had much lower nitrate concentrations when compared to the wells located at the 60 and 120 m line (Fig. 12). Due to mud in two of the deep wells, only two deep wells were sampled in 2013, having a mean nitrate concentration of 0.3 mg N L^{-1}, which did not change during the sampling period.

4. Discussion

During 2011, the water table level (as indicated by the water height in the control structure) was not increased or maintained during the application of DWM on ST. However, total annual flow for ST was reduced by 27% compared to the predicted flow based on drainage area alone, as other studies have done. Overall these results agree with those reported in the literature, in which tile flow is clearly reduced in the tile under DWM compared to the FD tile (e.g., Evans et al., 1995; Skaggs et al., 2010). Cooke and Verma (2012) reported a range of 30–96% in tile flow reduction for four fields under DWM compared to FD in a paired watershed scheme. Drury et al. (2009) reported a 29% tile flow reduction during DWM; however, surface runoff was increased and total annual flow reduction was only 11%. To avoid lateral seepage, Drury et al. (2009) used small plots that were isolated with plastic sheets, and they concluded that deep percolation was the fate of the retained water.

During 2012, the water table level (based on well water height) was increased and maintained during the application of DWM on NT (Fig. 7). However, the area of influence was only 2 ha (out of a total of 23 ha for the NT system). This area of influence was determined by comparing the response of the well water height to the control structure water height, which corresponded to the three wells closest to the NT control structure. Total annual flow for ST on an area basis was 25.2 cm which was nearly 200% greater than the annual flow (8.7 cm) in the adjacent river (the Upper Salt Fork of the Vermillion River). It was at this point we recognized a problem with our study. Upon closer inspection of tile flow rates after raising the stoplogs in NT, it appeared that tile water had flowed from the DWM tile (NT) to the FD tile (ST) in 2012 (Fig. 6). Although we did not discover this flow pathway immediately due to little precipitation and tile flow during the period of DWM in 2011, with the greater drainage area and flow of NT, the influence of DWM on the free draining ST was pronounced in 2012. If the lateral seepage of water from the DWM to the FD tile had not been discovered, our use of the paired watershed approach would have greatly inflated the overall performance of this technique. Recently, Rozemeijer et al.(2016) used high frequency monitoring of water fluxes and found that shallow groundwater flowed directly to a nearby ditch during a period of DWM. It may be that lateral seepage from adjacent drainage systems has occurred (possibly unnoticed) in other studies of DWM.

Comparing the combined total annual tile flow of ST and NT with Tile A (reference tile), we measured 12% greater flow from ST plus NT in 2012 than was predicted even when DWM reduced flow in one of the paired tiles (NT) (Fig. 4). Given the relatively small volume of tile flow during 2012 this was not a large amount of water and was not thought to be an important difference. However, our research site received 25 mm of rain on 3 March 2012, while the site of the reference tile received no rain that day. This one flow event that occurred at our research site but not at the reference tile site could account for the discrepancy between measured and predicted (Fig. 4).

In this study, nitrate yields were proportional to tile flow; therefore, nitrate yields were reduced similarly to flow when comparing the DWM field to the FD field. In 2011 the combined subsurface runoff from both tile drainage systems was 34 cm, yielding 33.9 kg N ha^{-1}. During 2012, tile nitrate yield was 13.5 kg N ha^{-1} from 13 cm of subsurface runoff from both tiles combined.

Given our observation of lateral seepage in 2012 (and presumably 2011) between ST and NT systems, DWM was applied to the entire field in 2013. Raising the stoplogs in both water level control structures influenced a total area of greater than 6 ha. During the DWM period there was substantial precipitation that increased and maintained the water table at a constant level of 70 cm from the soil surface in both tile systems. During 2013, DWM influenced the water height of all wells. Well water heights responded quickly after rain, regardless of the various stoplog settings used during the experiment.

The wells in the 0 m line closest to the water level control structures (15.1 m on either side of structure) had the greatest response to DWM and paralleled the water heights in the control structure in 2013. This may indicate lateral movement of retained water, circumventing the structures and moving down gradient under the road and beyond. The two continuously monitored wells in the 60 m line directly across from the control structures also showed that the application of DWM to both tile systems was effective at retaining water in the field. However, the high water table conditions also generated interflow and ponding during precipitation events, especially in the lowest areas of the field where the water level control structures were located. Surface ponding and flooding may also have led to dilution of shallow well nitrate concentrations in 2013 as the wells in the 0 m line had the lowest nitrate-N concentrations of the 3 lines of wells (Fig. 12). Chloride concentrations in the wells were much lower in the 0 m line also suggesting dilution (data not shown) and not denitrification.

In 2013, most of the retained water was measured as tile flow after lowering the stoplogs and releasing the water on April 17 for the final time. Based on the reference tile A, we estimated approximately 10% (approx. 15,000 m^3) of the retained water was not accounted for as tile flow. This water may have been lost from the field due to seepage around the control structures and under the road to another tile system or via deep seepage to groundwater. Adding both drainage systems together in 2013, the nitrate load was 31.6 kg N ha^{-1} with 43 cm of subsurface runoff.

Across the 34 ha field, corn yields were 9.9 and 7.1 Mg ha^{-1} in 2010 and 2012. By adding NT plus ST, tile nitrate loads across the 34 ha field in 2011 and 2013 were 33.8 and 32 kg ha^{-1}, while total fertilizer N application rates were 230 kg ha^{-1}. These tile loads represent a loss of approximately 14% of the applied fertilizer N. Considering that fertilizer N use efficiency of corn is less than 40% (Cassman et al., 2002), these tile loads seem small, especially taking into account the supply of N via soil mineralization in these rich prairie soils. Although the N rate used in this study is above the recommended amount for corn after soybean based on the Iowa State N Rate Calculator (MRTN), it is likely that the act of side-dressing N on this farm has improved N use efficiency, decreasing nitrate leaching. Soybean yields were 3.5 and 3.4 Mg ha^{-1} in 2011 and 2013. Total N load from the 34 ha field was 13.4 kg ha^{-1} in 2012; however, annual tile flow volumes were least in 2012 compared with 2011 or 2013 (Fig. 4).

The nitrate concentrations collected from both tile outlets had two distinct patterns during the three years of monitoring. During 2010 and 2012 when corn was grown and fertilizer N was side-dressed at 180 kg N ha^{-1} in late April/early May of each year, there was a steady increase in tile nitrate concentrations from winter through early spring during the next year, followed by decreasing concentrations in late spring. Following soybean production, tile nitrate concentration changed little during the drainage season of 2012, with concentrations steady at about 10 mg N L^{-1}. Following the severe drought of 2012, storm events in September and October produced tile flow with unusually low nitrate concentrations (as low as 1 mg N L^{-1}) (Fig. 3). It is possible that soil fissures and cracks due to the drought led to preferential flow of rainwater passing quickly through the soil and into the tile lines with limited contact with the soil matrix. We speculate that the long-term no-till practice at this site improved soil structure, increasing infiltration rates, and enhancing preferential flow. Overall, this variability in tile nitrate concentrations among years and crops is due to factors such as the timing of N fertilizer application, the effect of drought on soil permeability, and the distribution and intensity of precipitation (Jaynes and Colvin, 2006).

Tile water quality samples collected during this three year study demonstrated that increasing the water table level of the field had no measureable effect in the reduction of tile nitrate concentrations even after maintaining a high water level, indicating little if any denitrification. In addition, when taking the average nitrate concentration from all wells across a given tile system, the nitrate concentration is similar to the observed concentration at the main tile outlet. Dinnes et al. (2002) pointed out that in order to reduce nitrate via denitrification, DWM should be applied during the growing season when soil temperatures are high, but producers would need to stay vigilant and remove stoplogs if field flooding was likely. Additionally, other studies evaluating DWM during the growing season investigated the benefits of DWM on crop yield, but results have been mixed (Cooke and Verma, 2012; and Jaynes 2012).

Strock et al. (2010) suggested that DWM efficiency depends on the correct drainage design in concordance to the soil type and topography of the field in order to obtain best results. Others have suggested that the redesign of a subsurface tile drainage systems such that mains go up slope and laterals are on the contours could improve the efficiency of DWM in retaining tile water (Ehmke, 2013). We observed numerous precipitation events during the period of DWM that produced bypass flow due to sufficient head pressure from the laterals going up slope. Thus, our results may have been influenced by the fact that we used an existing tile system rather than installing a tile system designed to maximize DWM performance.

5. Conclusions

When DWM was imparted on both tile drainage systems in 2013, we were able to retain tile water as indicated by ground water heights in shallow wells throughout the fields. We estimated an area of influence at approximately 6 ha, which was 20% of the total drained area (NRCS minimum requirement). However, when we released the retained water by lowering the stoplogs, the majority of the retained water was accounted for. Therefore, we estimated that only 10% of the flow and nitrate load was reduced when both tiles were under DWM. In addition, we found no evidence of denitrification within the field during the period of DWM.

Overall our results tell a cautionary tale in regard to the use and success of DWM in fields with existing tile systems. During our first two attempts at DWM in 2011 and 2012, we found that we were forcing retained water to exit out the neighboring tile system during the period of DWM. This is particularly worrisome from a research perspective as many DWM studies use the paired watershed approach and have not investigated the fate of the retained water. In our study, we would have greatly overestimated the reduction in flow from DWM due to the inflated flow from lateral seepage to the FD tile. Furthermore, this scenario could possibly occur whereby one farmer might employ DWM on a tile, while laterally shunting shallow groundwater to the next nearest neighbor's tile. The findings observed in this study demonstrate the limitations and challenges of using DWM on existing tiles to reduce tile flow and nitrate load when other tile drainage systems are in close proximity (15 m).

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