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DRAINMOD-simulated performance of controlled drainage across the U.S. Midwest

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ABSTRACT

Controlled drainage (CD) has recently been proposed as a best management practice for reducing nutrient export from drained cropland in the U.S. Midwest to the Mississippi River and the Gulf of Mexico. We conducted a 25-year simulation study using the hydrological model, DRAINMOD, and the carbon and nitrogen (N) model, DRAINMOD-NII, to evaluate the performance of CD at 48 locations across the U.S. Midwest. Hydrological and Nitrogen predictions of this simulation study were compared to RZWQM-DSSAT predictions by Thorp et al. (2008). Simulation results showed that CD reduced annual subsurface drainage by 86 mm (30%) and annual N drainage losses by 10.9 kg N ha^{-1} (32%), on average over the 48 sites. DRAINMOD predicted highest reductions in drain flow at the south and southeast locations and lowest reductions at the northwest locations. The large reductions in drain flow in the south and southeast locations resulted in a large increase in surface runoff, which could increase soil erosion and sediment transport to surface water. In the north and northwest locations, the smaller amount of water that did not pass through the drainage system because of CD was primarily lost as evapotranspiration. DRAINMOD-NII predictions of annual reductions in N drainage loss followed the same trend of annual reductions in drainage flow. DRAINMOD-NII predictions show that reductions in N drainage loss under CD were mainly attributed to increase in denitrification. The declining trend in predicted annual denitrification from the southern to the northern locations of the Midwest region is most likely attributed to the lower temperature and less precipitation at the northern locations. RZWQM-DSSAT predicted reductions in annual drainage and N loss under CD conditions showed a similar trend to DRAINMOD/DRAINMOD-NII predictions. RZWQM-DSSAT, however, predicted substantially higher reductions in both drain flow (regional average of 151 mm yr^{-1}, 53%) and N drainage losses (regional average of 18.9 kg N ha^{-1} yr^{-1}, 51%). The discrepancies between DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT predictions of annual reductions in drain flow and N loss under CD conditions were caused by differences in model predictions of individual components of the water and nitrogen balances under both free drainage and controlled drainage scenarios. Overall, this simulation study showed that climate variation across the region has a substantial impact on CD efficacy for reducing N drainage loss.

1. Introduction

Agricultural drainage is essential for crop production on over 40 million ha, or about 25% of cropland in the United States. Drainage improves trafficability, providing timely access for performing field operations such as tillage, planting, and harvesting. More importantly, drainage removes excess water in the plant root zone, minimizing plant stress due to excess water and improving crop yield (Evans and Fausey, 1999). Subsurface drainage also reduces surface runoff, sediment losses and the movement of contaminants attached to the sediment, such as pesticides and phosphorus, into surface waters (Skaggs et al., 1994). Drainage, however, significantly alters the hydrology and nitrogen (N) cycling in naturally poorly drained soils. It lowers the water table and increases soil aeration, which increases soil organic matter decomposition (and associated N mineralization/immobilization) and decreases den-

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Table 1
Key input parameters of DRAINMOD model.

Drainage system parameters					
Drain depth (cm)	145				
Drain spacing (m)	27.4				
Drainage coefficient (cm day $^{-1}$)	1.4				
Effective drain radius (cm)	1.1				
Maximum surface storage (cm)	0.5				
Depth to restrictive layer (cm)	299				
Deep seepage parameters					
Restrictive layer thickness (cm)	200				
Piezometric aquifer head (cm)	200				
Restrictive layer conductivity (cm h^{-1})	0.0006				
Soil properties					
Layer depth (cm)	Clay (%)	Silt (%)	θ_s (cm^3 cm^{-3})	θ_{pwp} (cm^3 cm^{-3})	K_{sat} (cm h^{-1})
0–15	45	33	0.56	0.30	3.5
15–60	46	33	0.54	0.29	3.5
60–120	24	29	0.44	0.24	3.5
120–299	25	40	0.32	0.18	3.5
Soil temperature parameters					
Air temperature below which precipitation is snow (°C)	0.0				
Snowmelt base temperature (°C)	1.0				
Critical ice cover at which infiltration stops (cm^3 cm^{-3})	0.2				
Temperature at profile bottom (°C)	9.11				
Snowmelt Coefficient (mm d^{-1} °C^{-1})	5.00				

θ_s, θ_{pwp} are volumetric soil water content at saturation and permanent wilting point, respectively, *K*sat is lateral saturated hydraulic conductivity

itrification. The net result of artificial drainage is an increase in subsurface drainage flow rates and N leaching losses to receiving surface waters.

Nitrogen (N) losses from drained cropland in the U.S. Midwest have been identified as one of the main sources of N leading to the hypoxic conditions in the Gulf of Mexico (Petrolia and Gowda, 2006; Turner et al., 2008; Rabalais et al., 2007, 2014). There are over 16 million ha of artificially drained land in crop production in the Midwest, with five states (Illinois, Indiana, Iowa, Ohio, and Minnesota) accounting for over 50% of the U.S. land planted to corn and soybean (Petrolia and Gowda, 2006). Nitrogen losses from drained corn and soybean fields in the Midwest states make up a significant portion of the estimated 1.6 million metric tons of N discharged annually into the Gulf of Mexico (Scavia et al., 2004; Turner and Rabalais, 2003).

Achieving sustainability of crop production on drained land hinges upon the adoption of effective and economically feasible management practices that minimize nutrient export from drained lands without adversely affecting crop yield or increasing production cost. Drainage water management (DWM), also referred to as controlled drainage (CD), is a promising practice that is recently proposed as a best management practice (BMP) for reducing N export from drained cropland in Midwestern U.S.

Controlled drainage involves the use of an overflow control device (drainage water control structure or flashboard riser) at the drainage outlet that regulates the drainage intensity by raising and lowering the drainage outlet to better match the need for drainage in the agricultural field. This drainage water control mechanism reduces drainage volumes which decreases the edge-of-field mass loss of N to receiving surface waters (Evans et al., 1995; Evans and Skaggs, 2004; Skaggs et al., 2010; Skaggs et al., 2012). Additionally, CD raises the water table increasing anaerobic conditions in the soil profile which favors denitrification (Wesström and Messing, 2007; Skaggs et al., 2010). Lastly, it has been observed that careful management of CD systems during the crop growing season could lead to increasing crop yield and N uptake, especially under dry conditions (Poole et al., 2013). Achieving the yield benefits of CD requires proper management of the drainage systems during the growing season to avoid potential yield losses due to excessive water stresses. The water quality benefits of CD are mostly achieved by managing the drainage outlets during late fall, winter and early spring, when the practice has little or no effect on crop yield. The practice is applicable to both open-ditch and subsurface tile drainage systems.

Research conducted in the late 1970′s and 1980′s have shown that CD can substantially reduce the export of N and P to surface water from drained lands in the North Carolina Atlantic Coastal Plains by over 40% and 25%, respectively (Gilliam et al., 1979; Skaggs and Gilliam, 1981; Evans et al., 1995). As a result of this research, CD was accepted in the mid-1980s as a best management practice (BMP) for reducing nutrient losses to surface waters, with the control structures cost-shared by the state of North Carolina.

Recently, the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture has launched a national initiative for large scale adoption and implementation of CD in the Midwest to reduce N export from drained cropland to the Mississippi River Basin. The performance of CD depends upon several factors, including climatological conditions (precipitation and temperature), soil type (soil texture and organic matter content), topography, cropping system and farming practices (crop rotation, fertilization, tillage), and drainage system design (drain depth and spacing). Thus, the effectiveness of CD is expected to vary from location to location and from year to year. So, the reported performance of CD in the U.S. Southeast cannot be simply extrapolated to other geographic regions such as the U.S. Midwest. Moreover, the magnitude of N losses in drainage water, and the effect of CD on those losses are expected to vary among locations within the Midwest region.

The hydrological and water quality effects of CD are not well documented for the drained cropland of the U.S. Midwest. In Illinois, Pitts et al. (2004) reported 40% reduction in N drainage loss caused by implementing CD practice. In Ohio, Fausey (2005) found that CD reduced drainage outflows by 41% and N losses by 46%. More recently, field experiments have been conducted at several locations across the Midwest to study the effects of CD on N losses from drained croplands to surface waters (e.g. Adeuya et al., 2012; Cooke and Verma, 2012; Helmers et al., 2012; Jaynes, 2012; Gunn et al., 2015). These studies reported that CD reduces annual drainage flow and NO_3-N losses by 17% up to 90%. This large variation in cropping system response to CD was mainly attributed to spatial and temporal variations in weather, differences in soil types, and the level of management of the control structures in each experimental site. Despite this effort, the long term impacts of the large scale application of CD across Midwestern U.S. cannot be assessed by field experiments only. Computer simulation models can be cost effective and reliable tools for assessing the performance of CD as influenced by climatological, soil, and management factors. Ale et al. (2009) simulated the effect of CD on hydrology and crop yield at the Purdue University Water Quality Field Station (WQFS) using the drainage water management model, DRAINMOD. Model predictions showed that CD reduced annual drainage by 60% with no significant effect on crop yield (Ale et al., 2009). Thorp et al. (2008), used the RZWQM-DSSAT model, calibrated for a corn and soybean production system on a subsurface drained Iowa soil, to simulate the performance of CD using 25 years of climatological data for 48 locations across the Midwest. Their analysis showed that CD has a high impact on reducing both drain flow (35–68%) and N drainage losses (33–51%).

This paper reports on a simulation study using the hydrological model, DRAINMOD, and the carbon and nitrogen companion model, DRAINMOD-N II, to evaluate the performance of CD across Midwestern U.S. at the same 48 locations previously simulated by Thorp et al. (2008) using the RZWQM-DSSAT model. The performance of the practice predicted by the DRAINMOD suite of models was compared to CD performance predicted by the RZWQM-DSSAT model (Thorp et al., 2008). The performance of CD across the U.S. Midwest predicted by the two widely used models, DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT, would provide information, critically needed for supporting the recent initiatives for the large scale implementation of CD in the Midwest to reduce nitrogen loss from drained cropland to the Mississippi River Basin. These model predictions, along with the results of available short-term experiments will help make guided decisions on where in the Midwest CD would be most effective and economically feasible.

2. Materials and methods

2.1. DRAINMOD description

DRAINMOD (Skaggs, 1980) is a field-scale hydrological model that was developed in early 1980s to simulate the hydrology of poorly drained high water table soils. It uses the water balance approach with functional relationships to describe the main hydrological processes and predict infiltration, evapotranspiration, water table fluctuation, subsurface drainage, surface runoff, and lateral and vertical seepage in response to given climatological conditions, crop rotation, soil type, and drainage system design and management. The model predicts infiltration using the Green-Ampt equation. Subsurface drainage is calculated using the Hooghoudt's equation when the water table is below the surface and Kirkham's equations for ponded surface conditions. Surface runoff is estimated as the difference between rates of precipitation and infiltration, once site-specific surface depressional storage is filled (Skaggs, 1999). Daily potential ET (PET) can be computed by the model using the temperature-based, Thornthwaite method or estimated by the user using any PET method and provided to the model as an input data file.

The model simulates heat flow using finite difference solution to the heat equation and predicts the temperature distribution throughout the soil profile. This enables the model to simulate hydrological processes in cold regions, such as Midwestern U.S., which is influenced by soil freezing and thawing, and snow accumulation and melt (Luo et al., 2000). The model uses the empirical stress-day index approach to simulate the effect of excess and deficit soil water stresses on crop yield (Skaggs et al., 2012). DRAINMOD is easy to use, requires relatively few inputs, and yet provides quite accurate predictions. The model has been widely used to study the effects of drainage design and management on crop yields (e.g. Evans et al., 1991; Wang et al., 2006; Thorp et al., 2009), erosion (e.g. Saleh, 1994), hydrology of high water table soils (e.g. Fouss et al., 1987; Skaggs et al., 1981; Wang et al., 2006; Thorp et al., 2009; Luo et al., 2010), and wetland hydrology (e.g. Skaggs et al., 2005; Jia and Luo, 2006). A detailed description of DRAINMOD is given by Skaggs et al. (2012).

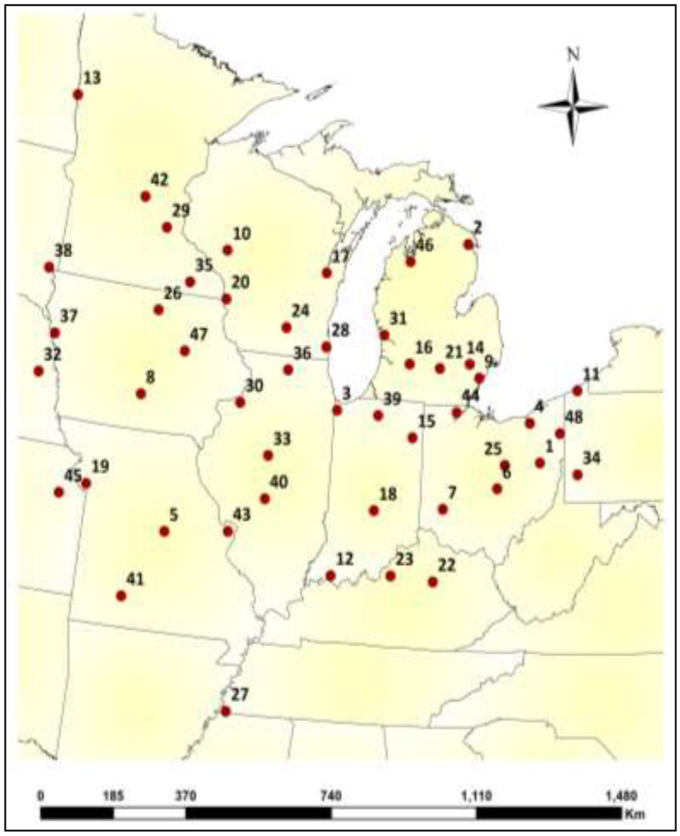
2.2. DRAINMOD-NII description

DRAINMOD-NII (Youssef, 2003; Youssef et al., 2005) is a field-scale, process-based model that simulates carbon (C) and N dynamics in drained cropland for a wide range of soil types, climatic conditions and farming practices. DRAINMOD-NII is a companion model to DRAINMOD. It simulates organic carbon (OC) dynamics using a C-cycle adapted from the CENTURY model (Parton et al., 1993). The soil C is represented by three soil organic matter pools (active, slow, and passive), two above-and below-ground residue pools (metabolic and structural), and a surface microbial pool. Each organic matter pool is characterized by OC content, potential rate of decomposition, and carbon-to-nitrogen ratio. Organic C decomposition is assumed to follow first order kinetics.

The model simulates a detailed N cycle that represents both mineral N (nitrate and ammoniacal forms) and organic N (ON) and their interaction as affected by C cycling. The model simulates wet atmospheric deposition, application of mineral N fertilizers, application of organic N sources such as plant residue and animal manure, plant N uptake, N mineralization and immobilization, nitrification, denitrification, ammonia volatilization, and N losses via subsurface drainage, deep seepage and surface runoff. Nitrogen reactive transport is simulated using a multiphase form of the one dimensional advection-dispersion-reaction (ADR) equation. Model predictions include daily concentrations of mineral N (i.e. NO_3 and NH_4) in soil solution and drainage outflow, OC content of the top 20 cm soil layer, and cumulative rates of simulated N processes on daily, monthly, and annual basis. DRAINMOD-NII has recently been applied successfully to a range of soils and locations across the U.S. (North Carolina: Youssef et al., 2006; Iowa: Thorp et al., 2009; Illinois: David et al., 2009; Minnesota: Luo et al., 2010; and Indiana: Ale et al., 2012) and Europe (Germany: Bechtold et al., 2007 and Sweden: Salazar et al., 2009).

2.3. Simulation approach

Thorp et al. (2007) evaluated the performance of the RZWQM-DSSAT model using ten years of measured hydrologic, water quality, and crop yield data for a corn-soybean agricultural system on tile drained silty clay loam/clay loam soils in central Iowa, U.S. (42.2° N, 93.6° W). During the ten year study period, controlled drainage was not implemented on the research site, meaning the outlets of the tile drains remained open during the entire period. Thorp et al. (2009) then evaluated the performance of DRAINMOD and DRAINMOD-NII models using the same data set. As part of the model evaluation, Thorp et al. (2009) compared the performances of RZWQM-DSSAT and DRAINMOD/DRAINMOD-NII. Thorp et al. (2008) used the RZWQ-DSSAT model, calibrated for the Iowa corn-soybean production system (Thorp et al., 2007), to simulate the performance of CD as affected by differences in climatic conditions, crop planting and harvesting dates, and N fertilization rates across the U.S. Midwest. They conducted the simulations using 30-



1	Akron	OH	17	Green Bay	WI	33	Peoria	IL
2	Alpena	MI	18	Indianapolis	IN	34	Pittsburgh	PA
3	Chicago	IL	19	Kansas City	MO	35	Rochester	MN
4	Cleveland	OH	20	Lacrosse	WI	36	Rockford	IL
5	Columbia	MO	21	Lansing	MI	37	Sioux City	IA
6	Columbus	OH	22	Lexington	KY	38	Sioux Falls	SD
7	Dayton	OH	23	Louisville	KY	39	South Bend	IN
8	Des Moines	IA	24	Madison	WI	40	Springfield	IL
9	Detroit	MI	25	Mansfield	OH	41	Springfield	MO
10	Eau Claire	WI	26	Mason City	IA	42	St. Cloud	MN
11	Erie	PA	27	Memphis	TN	43	St. Louis	MO
12	Evansville	IN	28	Milwaukee	WI	44	Toledo	OH
13	Fargo	ND	29	Minneapolis	MN	45	Topeka	KS
14	Flint	MI	30	Moline	IL	46	Trav. City	MI
15	Fort Wayne	IN	31	Muskegon	MI	47	Waterloo	IA
16	Gr. Rapids	MI	32	Omaha	NE	48	Youngstown	OH

Fig. 1. Locations of the 48 sites of the US Midwest included in the simulations, after Thorp et al., 2008.

years of historical climate data (1961–1990) for 48 locations across the Midwest (Fig. 1). Due to limitations in the interface of RZWQM-DSSAT model, Thorp et al. (2008) dropped the first 5 years of the simulations from the analysis.

Following the same modeling approach by Thorp et al. (2008), we used DRAINMOD and DRAINMOD-NII models, calibrated for the Iowa crop production system (Thorp et al., 2009), to conduct a thirty year simulation (1961–1990) of the hydrology, C and N dynamics, and crop yields for each of the 48 Midwestern locations (Fig. 1) under both free drainage (FD) and CD scenarios for the same soil type, crop rotation, and drainage design across different sites. This approach was followed to focus on the effect of geographic location on the performance of CD across Midwestern U.S. Using the calibrated parameters for the Iowa site, which were obtained by Thorp et al. (2009) enabled us to compare CD performance predicted by the two models, DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT.

The simulated soil consisted of an organic matter rich surface soil with a relatively poorly drained deep soil profile, underlain by a semi-impermeable layer allowing for vertical downward seepage into the groundwater aquifer. Key model inputs characterizing soil properties were set similar to values used by Thorp et al. (2009). The simulated drainage system consists of subsurface drains 145 cm deep, spaced 27.4 m apart. Maximum surface storage; a parameter that controls surface runoff rates, was set to 0.5 cm assuming a good surface leveling. Table 1 lists key model inputs characterizing drainage system design, soil properties, and snow accumulation and melt processes.

Table 2
State-wide average planting and harvesting dates for corn and soybean, and state-wide timing and rate of nitrogen (N) fertilizer application for corn (adapted from Thorp et al., 2008).

State	Corn			Soybean	
	Plant	Harvest	N Rate	Plant	Harvest
	DOY	DOY	Kg N ha^{-1}	DOY	DOY
Illinois	117	282	174	138	280
Indiana	123	293	165	138	283
Iowa	122	295	144	138	279
Kansas	118	271	158	143	287
Kentucky	112	267	181	152	294
Michigan	130	301	138	144	287
Minnesota	124	297	138	140	280
Missouri	111	268	175	145	292
Nebraska	124	295	152	140	281
North Dakota	130	299	125	143	278
Ohio	124	302	181	137	283
Pennsylvania	130	290	91	141	304
South Dakota	130	299	118	145	282
Tennessee	108	260	175	149	299
Wisconsin	132	304	112	145	288

The simulated cropping system includes corn, planted in even years, and soybean, planted in odd years. Simulated planting and harvesting dates (Table 2) were based on the state and county level National Agricultural Statistics Service (NASS) data for crop development and management across the region (USDA, 2007). For the CD scenario, the overflow level of the drainage water control structure was set to a depth of 30 cm during fall, winter, and early spring. Four weeks before planting, the overflow level was lowered to the drain depth (145 cm), three weeks after planting the level was raised to a depth of 60 cm and remained at this depth during the crop growing season. Two weeks before harvesting, the overflow level was lowered again to the drain depth and one week after harvesting the overflow level of the structure was raised to the off growing season depth of 30 cm. This is a typical management scheme to reduce drainage intensity when the land is fallow, operate the drainage system at maximum capacity to provide trafficable conditions for field operations (e.g. planting and harvesting), and provide adequate drainage during the crop growing season (Ale et al., 2012). The levels of the control structure and the timing of adjusting these levels may slightly vary. The timings and the levels used in this study were selected to match the timings and levels used by Thorp et al. (2008) to allow for comparison between predictions of DRAINMOD/DRAINMOD-NII and RZWQM models.

Thirty years of historical measured climate data (1961–1990), including hourly precipitation, in addition to daily minimum and maximum temperatures, wind speed, solar radiation, and relative humidity, were obtained from the National Solar Radiation Database (NREL, 1995). These climatological data were used to calculate the daily PET according to the FAO Pennman-Monteith method (Allen et al., 1998), which are saved in DRAINMOD compatible input files.

Similarly, model inputs required to simulate nitrogen and carbon dynamics were set according to Thorp et al. (2009). Table 3 lists key input parameters of DRAINMOD-NII. Fertilization and tillage management were set to describe common practices implemented for different locations. During corn years, nitrogen fertilizer was applied seven days before planting at rates equal to the five-year (2001- 2006) average (Table 2) according to the data retrieved by Thorp et al. (2008) from the USDA Economic Research Service USDA (2008). Tillage practices were set similar among the 48 sites and comprised spring field cultivator operations for site preparation one day before planting, and fall tillage consisted of chisel plowing following harvest operations.

Table 3
Key input parameters of DRAINMOD-NII model.

Crop biochemical composition	Corn	Soybean
Potential yield (Kg ha^{-1})	12000.0	3500.0
Harvest index	0.52	0.40
Root-to-shoot ratio	0.12	0.10
Grain N (%)	1.2	5.9
Shoot and root N (%)	0.55	2.2
Shoot and root carbon (%)	44.0	44.0
Shoot lignin (%)	3.50	9.10
Root lignin (%)	8.30	24.70
Nitrogen transport and transformations		
Longitudinal dispersivity (cm)	25.0	
Tortuosity	0.5	
	Nitrification	Denitrification
Maximum reaction rate (μg N g^{-1} soil d^{-1})	14.0	0.7
Half saturation constant†	10.0	40.0
Optimum temperature (◦C)	25.0	30.0

† Units are μg NH_4-N g^{-1} soil for nitrification, and mg NO_3-N l^{-1} for denitrification.

2.4. Comparison to RZWQM-DSSAT

As stated earlier, RZWQM-DSSAT was previously used to assess CD performance across the same 48 sites (Fig. 1) for the same climate time span (Thorp et al., 2008). Results of RZWQM-DSSAT simulations published by Thorp et al. (2008) were compared to DRAINMOD and DRAINMOD-NII predictions obtained in this study. This section provides a brief comparison between the two models, highlighting the similarities and differences in simulating key hydrological and biogeochemical processes. Understanding these similarities and differences is helpful for comparing CD performance predicted by both models and explaining the differences in these predictions.

Similar to DRAINMOD, RZWQM-DSSAT simulates infiltration of water into the soil profile using Green-Ampt equation, deep seepage using Darcy's equation, and simulates tile drainage using Hooghoudt equation. On the other hand, RZWQM-DSSAT applies a numerical solution to Richards' equation in order to compute soil water distribution in the vadose zone, which is different from the empirical "drained-to-equilibrium" approach implemented in DRAINMOD. The former model uses the Shuttleworth-Wallace PET method (Farahani and DeCoursey, 2000), while the later model uses either Thornthwaite method (with monthly correction factors) or, as was the case in this application, reads daily PET input calculated outside the model using any PET method. In addition, RZWQM-

DSSAT does not simulate storage of water on the soil surface; rather, water that exceeds macropore infiltration is considered runoff.

The plant growth component of the RZWQM-DSSAT is a deterministic process-based module adapted from the widely used DSSAT crop models. These crop modules simulate, on a day-by-day basis, plant growth rate and mass accumulation and allocation as affected by temperature, soil water and nutrient status, as well as atmospheric CO_2 concentration. DRAINMOD simulation of crop yields is based on the empirical stress day index approach. The recently upgraded version of DRAINMOD, DRAINMOD-DSSAT (Negm et al., 2014), was not used in the current study. RZWQM-DSSAT differs from DRAINMOD-NII simulations of carbon and nitrogen dynamics. RZWQM-DSSAT applies the **O**rganic **M**atter and **N**itrogen (OMNI) module developed by Shaffer et al. (2000). Nitrogen transport within RZWQM-DSSAT is simulated using sequential partial piston displacement and mixing approach.

3. Results and discussion

3.1. Simulated effect of controlled drainage on hydrology

Table 4 summarizes the results of DRAINMOD hydrological simulations for the 48 locations averaged over the 25-year simulation period. As expected, the model predicted that CD would decrease subsurface drainage and increase surface runoff, evapotranspiration and vertical seepage, compared to conventional drainage with unmanaged outlets (FD). Model predictions show that CD reduced annual subsurface drainage by 8.6 cm yr^{-1} (30%), on average over the 48 sites. The model predicted a corresponding increase in surface runoff by 4.8 cm yr^{-1} (123%), evapotranspiration by 2.7 cm yr^{-1} (5%) and vertical seepage by 0.9 cm yr^{-1} (23%). Of the 8.6 cm yr^{-1} that did not pass through the drainage system because of CD, 56% was lost as surface runoff, 31% was lost as evapotranspiration, and 10% was lost via deep seepage. The predicted average water balance for the FD scenario indicated that 31.8%, 4.5%, 59.2%, and 4.5% of the 88 cm yearly average precipitation were lost via subsurface drainage, surface runoff, evapotranspiration, and vertical seepage, respectively. The corresponding predicted average water balance for the CD scenario shows a substantial decrease in subsurface drainage (22.1% of precipitation), compensated for by a substantial increase in surface runoff (10% of precipitation) and a slight increase in both evapotranspiration (62.5% of precipitation) and vertical seepage (5.5% of precipitation).

Controlled drainage was most effective in reducing drain flow at the south and southeast locations (Fig. 2a). The highest simulated reduction in drain flow occurred in Memphis, Tennessee (Table 4). For this location, CD reduced drain flow by 26.7 cm yr^{-1} (45%) and increased surface runoff, ET, and vertical seepage by 18.8 cm yr^{-1} (355%), 6.6 cm yr^{-1} (11%), and 1.2 cm yr^{-1} (29%), respectively. The second highest simulated reduction in drain flow occurred in Evansville, Indiana. Implementing CD at this location reduced drain flow by 16.3 cm yr^{-1} (39%) and increased surface runoff, ET, and vertical seepage by 10.8 cm yr^{-1} (292%), 4.2 cm yr^{-1} (7%), and 1.1 cm yr^{-1} (28%), respectively. The lowest simulated reduction in drain flow of 19% occurred at northwest locations in both Sioux City, Iowa and Sioux Falls, South Dakota (Fig. 2a and Table 4). For the Sioux City location, CD slightly reduced drain flow by 2.3 cm yr^{-1}, and slightly increased surface runoff, ET, and vertical seepage by 0.2 cm yr^{-1} (12%), 1.5 cm yr^{-1} (3%), and 0.6 cm yr^{-1} (17%), respectively.

The predicted fate of the water that did not pass through the drainage system under CD conditions varied across the region. The large reductions in drain flow associated with implementing CD in the south and southeast locations resulted in a large increase in surface runoff and only a modest increase in vertical seepage. For example, CD reduced drain flow at the Memphis location by 26.7 cm yr^{-1}. Of this amount, 70% was lost by surface runoff, 25% was lost through ET, and only 5% was lost through vertical seepage. The large increase in surface runoff could have negative impacts due to increased soil erosion and transport of sediment and contaminants attached to sediment including phosphorus and pesticides. In the north and northwest locations where CD is relatively less effective (drain flow reductions <20%), the water that did not pass through the drainage system because of CD was primarily lost through ET. Of the 2.3 cm yr^{-1} reduction in drain flow due to implementing CD at Sioux City, 65% was lost through ET, 26% was lost through vertical seepage, and only 9% was lost via surface runoff. These results indicate that CD does not significantly increase vertical seepage for this soil and boundary conditions as was hypothesized by Skaggs et al. (2010) for a site in North Carolina. These findings, however, cannot be generalized as the effect of CD on field hydrology varies with soil type and boundary conditions on the site. Another simulation study with different soils would be very useful in assessing the effect of CD on field hydrology and especially on vertical seepage for different soils.

Overall, it is clear that climate variation across the region has a substantial impact on CD efficacy for reducing drainage flow. Normally, higher annual precipitation and average annual temperatures were associated with higher drainage rates as well as higher flow reductions under the CD scenario in the south and southeast locations (Fig. 2). Flow reductions in the North and northwest locations were significantly lower due to lower annual precipitation and prolonged freezing fallow periods (November till early March) when CD is mostly applied for water quality benefits.

DRAINMOD hydrological predictions were used to develop linear regression equations for estimating long term average annual drainage flow under FD and CD scenarios across the Midwest region (Eqs. (1) and (2)). Precipitation was found to be the only explanatory variable that has statistically significant effect on predicting drainage flow. The R^2 values were 0.95 and 0.89 for the regression equations of FD and CD scenarios, respectively, indicating that precipitation is an adequate predictor of drainage flow across the Midwest region. It should be noted that the simulations were conducted with one drainage intensity (drain depth and spacing). Drainage intensity would likely also significantly impact annual subsurface drainage if it had been tested.

$$D_{FD} = -29.67 + 0.6548R \quad (1)$$

$$D_{CD} = -13.92 + 0.3775R \quad (2)$$

where D_{FD} and D_{CD} are the long term average annual drainage (cm yr^{-1}), under FD and CD scenarios, respectively, and *R* is the long term average annual precipitation (cm yr^{-1})

3.2. Simulated effects of controlled drainage on nitrogen cycle

The results of DRAINMOD-NII nitrogen simulations for the 48 sites are presented in Table 5. On average across the 48 locations, model predictions show that CD reduced N drainage losses by 10.9 kg N ha^{-1} yr^{-1} (32%), increased denitrification by 8.0 kg N ha^{-1} yr^{-1} (73%), increased plant uptake by 0.9 kg N ha^{-1} yr^{-1} (0.65%), increased N losses via surface runoff by 1.3 kg N ha^{-1} yr^{-1} (76%), and slightly decreased N losses via vertical seepage by 0.4 kg N ha^{-1} yr^{-1} (12%). The predicted fate of the 10.9 kg N ha^{-1} yr^{-1} reduction was as follows: 73% was denitrified, 12% was lost via surface runoff, and 4% was lost via deep seepage. Practically, CD did not affect N plant uptake and net N mineralization. These simulation results support the hypothesis that CD increases the anaerobic conditions in the soil profile, promoting denitrification and reducing N leaching losses. The small N concentrations in runoff water explain the modest increase in mass loss of N via surface runoff

Table 4
Yearly averages of measured precipitation and simulated subsurface drainage, runoff, ET, and vertical seepage for 48 locations across the U.S. Midwest.

City	State	Precip	Drainage			Runoff		ET		Seepage	
			FD	CD	ΔD (%)	FD	CD	FD	CD	FD	CD
		cm yr $^{-1}$			%	cm yr $^{-1}$					
Akron,	OH	92.7	30.4	22.1	27.3	3.4	8.1	54.4	56.8	3.9	5.1
Alpena,	MI	73.2	20.6	14.3	30.5	3.6	7.2	44.8	46.5	3.8	4.7
Chicago,	IL	91.7	29.4	20.0	32.0	3.7	8.5	54.3	57.6	3.9	5.0
Cleveland,	OH	93.0	26.9	19.6	27.2	2.3	5.7	59.3	62.1	3.9	4.9
Columbia,	MO	98.8	35.7	24.0	32.7	3.0	8.8	55.8	60.3	4.0	5.0
Columbus,	OH	96.8	32.7	23.7	27.7	3.8	8.7	55.7	58.5	4.0	5.2
Dayton,	OH	93.1	31.1	22.3	28.4	2.6	7.5	54.7	57.6	3.9	5.1
Des Moines,	IA	84.1	22.1	16.2	26.8	2.5	3.9	55.3	58.9	3.8	4.7
Detroit,	MI	82.9	21.2	13.9	34.6	4.0	7.2	53.4	56.4	3.8	4.8
Eau Claire,	WI	77.5	19.4	14.5	25.2	6.0	7.5	48.0	51.5	3.8	4.3
Face Erie,	PA	106.1	41.9	30.1	28.2	3.1	11.0	56.4	58.9	4.1	5.4
Evansville,	IN	109.5	41.9	25.6	38.9	3.7	14.5	59.5	63.7	4.0	5.1
Fargo,	ND	49.4	6.2	4.8	23.1	2.2	2.8	37.7	38.2	3.2	3.5
Flint,	MI	76.9	20.0	13.7	31.4	2.8	5.6	49.8	52.2	3.8	4.7
Fort Wayne,	IN	88.2	27.3	19.1	30.1	3.4	8.3	52.9	55.2	3.9	5.0
Grand Rapids,	MI	92.3	33.8	22.7	32.8	4.2	11.5	49.9	52.3	3.9	5.1
Green Bay,	WI	73.2	18.6	13.5	27.5	4.3	6.7	46.1	47.9	3.7	4.5
Indianapolis,	IN	100.2	34.8	22.8	34.4	4.0	11.5	56.9	60.1	4.0	5.0
Kansas City,	MO	96.8	32.9	23.0	30.0	3.5	7.8	56.0	60.5	4.0	5.0
Lacrosse,	WI	78.8	18.7	13.5	27.4	8.2	10.8	47.8	49.5	3.7	4.5
Lansing,	MI	77.8	23.0	16.1	30.0	2.7	6.4	47.9	50.0	3.8	4.8
Lexington,	KY	113.1	44.7	28.9	35.3	3.8	14.0	59.9	64.2	4.1	5.3
Louisville,	KY	112.8	43.7	26.8	38.7	3.7	14.1	60.6	65.8	4.1	5.3
Madison,	WI	78.2	20.1	14.8	26.3	4.6	7.1	49.3	51.4	3.8	4.5
Mansfield,	OH	100.8	43.3	32.7	24.5	4.3	12.4	48.4	49.5	4.1	5.5
Mason City,	IA	75.1	19.1	14.7	23.4	4.4	6.7	47.5	49.0	3.4	4.5
Memphis,	TN	131.8	58.9	32.2	45.3	5.3	24.1	62.8	69.4	4.1	5.3
Milwaukee,	WI	83.7	24.1	15.9	33.9	5.2	9.6	50.2	52.8	3.8	4.7
Minneapolis,	MN	72.0	14.6	10.7	26.3	4.4	5.9	49.2	50.8	3.6	4.1
Moline,	IL	99.2	34.9	23.4	33.0	5.0	11.4	54.9	58.6	4.0	5.2
Muskegon,	MI	82.9	29.1	19.8	32.0	3.5	9.2	46.0	48.4	3.9	4.9
Omaha,	NB	73.7	16.3	13.0	19.8	2.7	3.3	50.8	52.8	3.7	4.3
Peoria,	IL	91.9	31.5	21.0	33.5	3.1	8.5	52.9	56.7	4.0	5.1
Pittsburgh,	PA	93.7	26.6	18.9	28.9	3.1	6.7	59.3	62.4	3.9	4.9
Rochester,	MN	74.0	18.0	14.2	21.1	4.1	5.7	47.8	49.4	3.8	4.4
Rockford,	IL	94.1	34.2	22.9	33.0	5.2	12.4	50.3	53.0	4.0	5.2
Sioux City	IA	65.7	12.6	10.3	18.7	1.7	1.9	47.6	49.1	3.5	4.1
Sioux Falls,	SD	60.6	11.5	9.3	18.9	2.4	2.9	42.9	44.1	3.5	4.0
South Bend,	IN	104.9	37.9	26.2	30.7	7.2	14.9	55.4	57.9	4.0	5.2
Springfield,	IL	89.3	30.2	20.2	33.1	3.4	8.5	51.8	54.8	4.0	5.1
Springfield,	MO	109.3	42.4	27.4	35.5	4.4	12.7	57.9	63.3	4.1	5.2
St. Cloud,	MN	68.3	19.2	15.6	18.8	4.2	6.4	40.5	41.3	3.7	4.4
St. Louis,	MO	95.1	33.3	21.4	35.7	3.1	9.2	54.3	58.9	3.9	5.0
Toledo,	OH	83.7	25.7	18.1	29.6	3.6	8.0	49.9	52.0	3.9	4.9
Topeka,	KN	89.4	27.4	18.5	32.5	3.3	6.7	54.3	58.7	3.9	4.9
Traverse City,	MI	67.2	16.4	11.6	29.2	4.3	7.0	42.5	43.7	3.6	4.4
Waterloo,	IA	85.5	24.3	18.1	25.4	5.5	8.6	51.5	53.7	3.9	4.7
Youngstown,	OH	95.1	32.9	24.5	25.7	3.2	8.1	54.4	56.6	4.0	5.2
Average		**88.0**	**27.9**	**19.3**	**29.5**	**3.9**	**8.7**	**51.9**	**54.6**	**3.9**	**4.8**

FD, free (also referred to as conventional) drainage; CD, controlled drainage; ΔD (%), the percent of drainage reduction due to controlled drainage; ET, evapotranspiration.

despite the large increase in surface runoff induced by CD. The increase in predicted denitrification rates caused by CD resulted in a slight decrease in the predicted concentration of NO_3-N in groundwater (5% reduction), and a corresponding reduction in predicted NO_3-N mass losses via vertical seepage despite the modest increase in vertical seepage flux. These simulation results compare well to results of DRAINMOD-NII simulation by Skaggs et al. (2012) who assessed CD performance for an agricultural field in Springfield, Illinois. They reported 10.8 kg N ha^{-1} reduction in N leaching losses via subsurface drainage under CD conditions (33% reduction). The majority of N that did not leave the field via subsurface drainage were denitrified (71%) or lost via surface runoff (16%); while simulated CD effect on plant uptake, mineralization, deep seepage, as well as flow-weighted NO_3—N concentration were insignificant.

Similar to the simulated hydrology for the 48 sites, CD was most effective in reducing N drainage losses at the south and southeast locations and least effective at the north and northwest locations. The largest predicted reduction in N drainage losses occurred at Memphis, Tennessee. At this location, CD reduced N drainage loss by 31.8 kg N $ha^{-1}yr^{-1}$ (47%) and N losses via vertical seepage by 0.5 kg N $ha^{-1}yr^{-1}$ (14%), and increased denitrification by 20.3 kg N $ha^{-1}yr^{-1}$ (98%), N plant uptake by 3.9 kg N $ha^{-1}yr^{-1}$ (3%), and N losses via surface runoff by 3.8 kg N $ha^{-1}yr^{-1}$ (317%). The least reduction in N drainage losses occurred at Fargo, North Dakota. At this location, CD reduced N drainage loss by 1.4 kg N $ha^{-1}yr^{-1}$ (12%) and N losses via vertical seepage by 0.3 kg N $ha^{-1}yr^{-1}$ (10.3%), and increased denitrification by 1.5 kg N $ha^{-1}yr^{-1}$ (20%), N plant uptake by 0.6 kg N $ha^{-1}yr^{-1}$ (0.5%), and N losses via surface runoff by 0.2 kg N $ha^{-1}yr^{-1}$ (11%). The declining trend in predicted annual denitrification from the southern to the northern locations of the Midwest region may be attributed to the lower temperature and less precipitation at the northern locations. Denitrification reaction proceeds at slower rates at lower temperature. Also, the anaerobic conditions at the

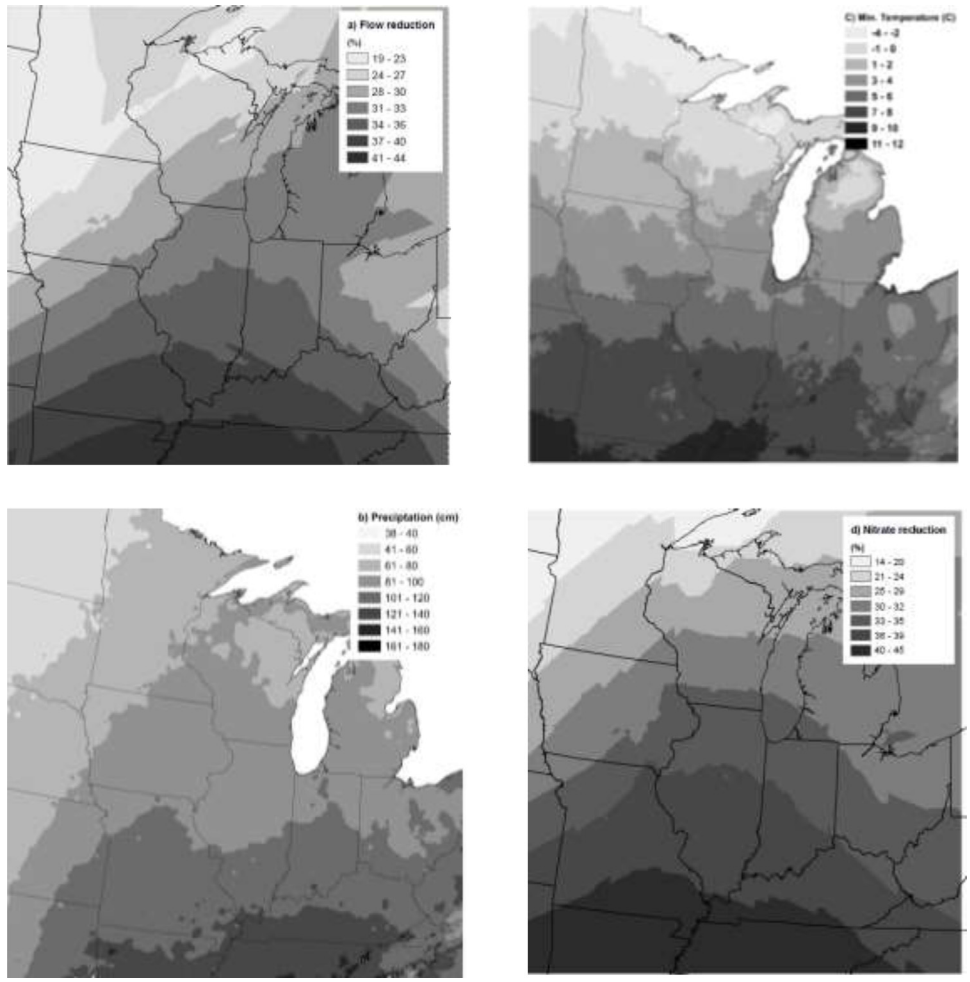


Fig. 2. Maps of Midwestern U.S. showing the spatial distribution of (a) CD-caused percent reduction in drainage flow; (b) long term mean annual precipitation, inches; (c) long term mean of minimum daily temperature, F°; (d) CD-caused percent reduction in nitrogen loss via subsurface drainage.

shallow soil profile, which favors denitrification is expected to occur less frequently as precipitation decreases.

The long term averages of DRAINMOD-NII predictions of annual losses of N across the 48 locations were used to formulate linear regression models for estimating these losses across the Midwest region. The annual average of daily minimum temperature, annual precipitation, and annual application rate of nitrogen fertilizer were found to have statistically significant effects on estimating annual N losses via drainage flow under both FD and CD scenarios. The developed regression equations are as follows,

$$NLOSS_{FD} = -30.52 + 2.7046T + 0.2768R + 0.1817\,N_{fer} \quad (3)$$

$$NLOSS_{CD} = -13.45 + 1.6662T + 0.0972R + 0.1286\,N_{fer} \quad (4)$$

where $NLOSS_{FD}$ and $NLOSS_{CD}$ are the annual losses via drain flow under FD and CD scenarios, respectively (kg N ha^{-1} yr^{-1}), T is the long term average of minimum daily temperature (°C), R is annual precipitation (cm yr^{-1}), and N_{fer} is the annual rate of N fertilizer application (kg N ha^{-1} yr^{-1}). The R^2 values for Eqs. (3) and (4) were 0.91 indicating that the three explanatory variables used to formulate the regression equations are adequate predictors of the response variable.

DRAINMOD and DRAINMOD-N II predicted that the implementation of CD across the 48 locations will reduce, on average over the 25 simulated years, drain flow by 30% and reduce N drainage loss by 32%. For the Memphis location, where CD was predicted to be most effective, percent reductions in drain flow and N drainage losses were 45% and 47%, respectively. These predictions support the hypothesis that CD does not significantly change nitrogen concentration in drainage water and thus the percent reduction in N drainage loss can be approximated by the percent reduction in drain flow. The predicted change in N cycling caused by CD indicates that the modest changes in N concentration in drainage water does not necessarily mean that the practice has a little impact on N dynamics in the system.

This set of simulations clearly predicts that CD increases denitrification and subsequently reduces NO_3 concentration in groundwater. At the same time, model predictions indicate that percent reductions in drain flow and N drainage losses are nearly equal on a percentage basis, which is consistent with the results of field experiments on CD (Skaggs et al., 2012). However, field experiments to date have not included a detailed study and accounting of N fate and internal cycling in the soil-water-plant system as affected by CD. The experimental verification of the predicted effect of CD on N balance for crop production systems on drained land would require a side-by-side comparison of both CD and FD scenarios, involving extensive measurements of mineral N concentrations in the root zone, in the shallow groundwater at different depths, and in drainage outflow. These experiments need to be conducted for a long enough time to capture the response of the system to changes in precipitation, cropping system, and N fertilization. Due primarily to limitations in the level of financial support required, none of the field experiments conducted on CD have included sufficiently intensive measurements over the time and range of conditions nec-

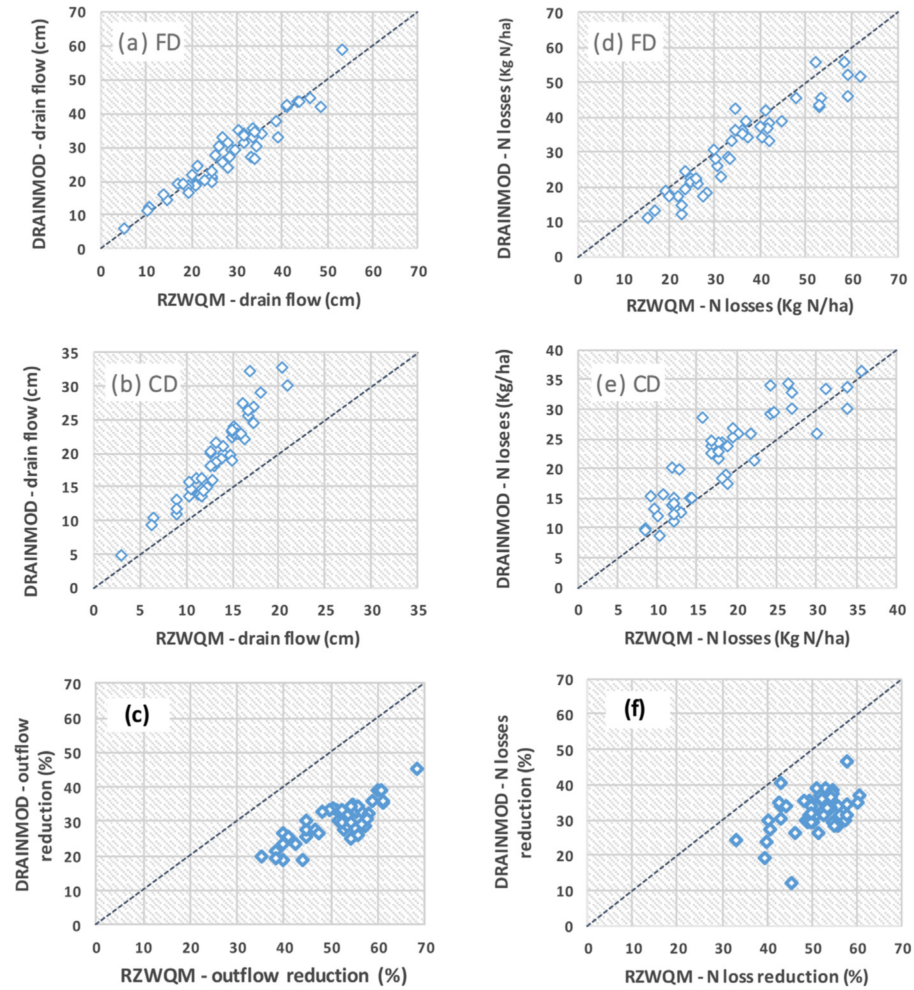


Fig. 3. Scatter plots of DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT predictions for the simulated 48 locations within Midwestern U.S. (plots a, b, and c compare predictions of annual drain flow under free drainage and controlled drainage scenarios, respectively; plots d, e, and f compare predictions of annual N losses under free drainage and controlled drainage scenarios; respectively).

essary to explain with certainty the effects of CD on N fate in drained cropland.

3.3. Comparison between DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT predictions

3.3.1. Model predictions of water and nitrogen budgets for the corn-Soybean agricultural system in Iowa

As stated earlier, modeling the CD performance across Midwestern U.S. using the two models followed the same approach and used input parameters that were obtained through the calibration and validation of both models using the same data set. This data set was collected for a corn-soybean agricultural system on tile drained soil in central Iowa, U.S. Before comparing the predictions of the two models across the 48 locations, a brief summary of the calibration and validation conducted by Thorp et al. (2009) for both models using the ten-year Iowa data set is given as it is relevant to the comparison of their predictions of CD performance across the entire Midwest region.

The water budgets predicted by the two models were similar but DRAINMOD predicted more surface runoff and less deep seepage than RZWQM (Thorp et al., 2009). Over the ten-year simulation period, both models predicted that annual ET and subsurface drainage represent 65% and 25% of annual precipitation, respectively. DRAINMOD predicted a total of 36 mm (4.7%) surface runoff and 39 mm (5.0%) vertical seepage. RZWQM predictions of total surface runoff and vertical seepage were 19 mm (2.5%) and 45 mm (5.9%), respectively. Statistical performance measures were similar for both models, indicating good agreement between measured and predicted drain flows. DRAINMOD's modeling efficiency values for predicting annual drain flow during calibration and validation periods were 0.92 and 0.91, respectively, indicating consistent model performance during both calibration and validation periods. The corresponding modeling efficiency values of RZWQM were 0.98 and 0.82, indicating more accurate predictions during calibration years and relatively less accurate predictions during validation years.

For the nitrogen simulations, DRAINMOD-NII predictions of N losses via subsurface drainage were more accurate than the values predicted by RZWQM-DSSAT model (Thorp et al., 2009). The modeling efficiency values for DRAINMOD-NII predictions of annual mass losses of nitrate via subsurface drainage during calibration and validation years were 0.94 and 0.95, respectively. The corresponding modeling efficiency values of RZWQM predictions dropped from 0.92 during calibration years to 0.21 during validation years. DRAINMOD-NII was capable of accurately predicting the fluctuation in annual N drainage losses as influenced by variability in precipitation for the simulated corn-soybean production system. Compared to RZWQM-DSSAT model, DRAINMOD-NII predicted higher N losses via subsurface drainage, surface runoff, and denitrification, higher mineral N input through mineralization, and

Table 5
Nitrogen fertilizer application rates and long term averages for nitrogen losses in subsurface drainage, denitrification, Plant uptake, runoff losses, and seepage losses.

City	State	N Rate	Drainage			Denitrification		Plant uptake		Runoff losses		Seepage losses	
			FD	CD	ΔD (%)	FD	CD	FD	CD	FD	CD	FD	CD
		kg N ha^{-1} yr^{-1}			%	kg N ha^{-1} yr^{-1}							
Akron	OH	181	38.3	25.7	32.9	11.5	21.1	154.8	154.6	1.9	3.2	3.7	3.2
Alpena	MI	138	12.3	8.7	29.0	4.3	6.1	150.1	149.8	1.3	2.3	1.7	1.7
Chicago	IL	174	36.1	23.6	34.7	11.8	21.4	148.0	149.1	1.7	2.9	3.6	3.1
Cleveland	OH	181	34.3	25.2	26.6	10.8	18.6	156.9	156.6	1.3	2.6	3.7	3.3
Columbia	MO	175	51.6	33.3	35.4	15.8	29.4	134.6	137.6	1.7	3.2	4.0	3.4
Columbus	OH	181	36.8	24.3	33.9	13.0	24.0	155.2	154.0	2.0	3.3	3.5	2.9
Dayton	OH	181	43.0	30.1	30.0	13.2	23.7	146.7	146.7	2.1	3.5	4.4	4.0
Des Moines	IA	144	28.4	18.7	34.0	12.1	19.5	140.5	141.9	0.8	1.3	3.6	2.8
Detroit	MI	138	36.2	24.7	31.7	11.9	19.5	112.2	114.7	3.5	5.1	4.8	4.3
Eau Claire	WI	112	19.5	13.7	29.8	7.3	12.1	131.8	131.8	2.7	3.2	2.6	2.3
Erie	PA	91	24.3	15.3	36.8	6.9	11.7	129.1	128.3	0.8	2.2	1.9	1.6
Evansville	IN	165	55.7	33.9	39.1	15.0	28.6	134.1	137.4	1.3	4.2	4.1	3.7
Fargo	ND	125	11.3	9.9	12.4	7.4	8.9	124.5	125.1	1.8	2.0	2.9	2.6
Flint	MI	138	21.9	15.0	31.6	7.9	12.0	142.3	142.6	1.5	2.7	3.0	2.7
Fort Wayne	IN	165	34.3	23.5	31.6	11.5	19.5	146.1	146.7	1.6	3.5	3.7	3.4
Gr. Rapids	MI	138	30.8	20.0	35.0	8.6	15.2	136.2	137.5	1.2	3.1	2.7	2.6
Green Bay	WI	112	13.3	9.4	29.3	5.1	7.8	139.1	139.8	1.5	2.2	1.9	1.8
Indianapolis	IN	165	38.9	25.7	33.9	11.8	20.2	150.5	151.4	2.2	4.1	3.5	3.2
Kansas City	MO	175	46.2	29.9	35.4	16.5	29.1	133.7	134.5	1.5	2.5	4.0	3.4
Lacrosse	WI	112	18.0	11.9	33.7	7.6	11.6	135.8	137.1	2.2	2.9	2.4	2.2
Lansing	MI	138	22.5	15.4	31.5	7.9	12.1	141.9	142.9	2.0	3.7	2.7	2.4
Lexington	KY	181	45.4	29.1	35.8	13.9	26.6	153.0	152.9	1.5	3.5	3.3	2.9
Louisville	KY	181	55.7	34.1	38.8	16.5	32.1	140.1	141.9	1.2	4.0	4.1	3.6
Madison	WI	112	18.7	13.2	29.6	7.3	10.7	133.8	135.0	2.4	3.0	2.6	2.4
Mansfield	OH	181	42.6	28.4	33.2	11.3	21.2	153.6	151.6	1.5	3.4	3.2	3.0
Mason City	IA	144	21.6	15.0	30.5	8.1	13.3	143.7	143.6	2.6	3.3	3.0	2.5
Memphis	TN	175	68.0	36.2	46.8	20.7	41.0	126.6	130.5	1.2	5.0	3.6	3.1
Milwaukee	WI	112	21.0	14.0	33.5	7.2	11.2	127.2	128.2	1.5	2.9	2.3	2.2
Minneapolis	MN	138	25.9	18.1	30.2	9.7	15.4	130.3	132.3	3.4	4.7	4.3	3.5
Moline	IL	174	38.7	24.4	36.8	12.9	24.2	146.7	146.4	1.6	3.2	3.4	2.7
Muskegon	MI	138	28.1	19.7	30.0	8.1	13.3	129.4	129.8	1.3	2.9	2.8	2.8
Omaha	NB	152	28.0	21.2	24.5	13.1	18.5	133.8	134.9	2.5	2.8	4.6	3.9
Peoria	IL	174	41.8	26.7	36.1	13.6	25.8	146.3	146.5	1.5	2.9	3.9	3.3
Pittsburgh	PA	91	18.3	13.1	28.6	7.4	12.3	136.6	136.3	1.7	2.4	2.0	1.8
Rochester	MN	138	17.4	12.6	27.7	7.1	11.2	142.2	145.8	1.3	1.7	2.4	2.1
Rockford	IL	174	35.4	21.6	39.0	11.2	20.6	147.9	148.2	1.9	4.1	3.0	2.5
Sioux City	IA	144	22.9	17.4	24.0	10.7	15.6	135.6	137.1	1.7	1.8	4.1	3.6
Sioux Falls	SD	118	17.2	13.9	19.1	8.2	10.8	127.7	128.5	2.1	2.2	3.1	2.9
South Bend	IN	165	37.5	24.6	34.3	11.2	20.7	146.2	146.6	1.0	2.7	3.0	2.7
Springfield	IL	174	45.4	29.3	35.5	14.6	27.1	142.0	144.9	2.2	3.6	4.6	3.9
Springfield	MO	175	52.4	32.6	37.8	15.9	30.6	135.4	139.2	1.7	3.6	3.7	3.4
St. Cloud	MN	138	15.0	11.0	26.9	6.1	10.4	143.9	142.6	0.9	1.3	2.0	1.8
St. Louis	MO	175	53.2	33.6	36.8	17.1	31.7	129.8	132.9	1.4	3.4	4.6	3.9
Toledo	OH	181	33.0	22.4	32.1	10.4	18.1	148.9	149.0	2.1	3.7	3.7	3.4
Topeka	KN	158	43.4	25.8	40.7	16.2	28.2	133.0	135.8	1.6	2.4	4.4	3.5
Trav. City	MI	138	17.2	12.3	28.8	6.5	10.0	140.8	141.2	2.1	3.2	2.7	2.6
Waterloo	IA	144	22.6	14.9	33.7	9.5	15.7	145.8	146.0	1.5	2.1	2.8	2.3
Youngstown	OH	181	33.3	22.8	31.5	10.4	18.8	156.6	156.3	1.2	2.6	3.1	2.7
Average		**151.8**	**32.4**	**21.4**	**32.3**	**10.9**	**18.9**	**140.0**	**140.9**	**1.7**	**3.0**	**3.3**	**2.9**

FD, free (also referred to as conventional) drainage; CD, controlled drainage; ΔD (%), the percent of nitrogen losses reduction in subsurface drainage due to controlled drainage.

lower N fixation and N losses via deep seepage and ammonia volatilization (Thorp et al., 2009).

3.3.2. *Model predictions of water and nitrogen budgets across Midwestern U.S*

Both DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT predicted a declining trend in the effectiveness of CD from the south to the north within the U.S. Midwest region. The two models, however, differed substantially in the predicted magnitude of reduction in both annual drain flow and N drainage loss. DRAINMOD predicted that CD would reduce average annual drain flow by a range of 19%-45% with an overall average of 30% across the region. In contrast, RZWQM-DSSAT predicted much larger reductions in annual drain flow ranging from 35% to 68% with an average of 53% across the region. Average reductions in annual N mass loadings predicted by DRAINMOD-NII ranged from 12% to 47% with an overall average of 32% across the region. Similar to drainage predictions, predicted reductions in annual N mass loadings by RZWQM-DSSAT were much larger than DRAINMOD-NII predictions, ranging from 33% to 58% with an overall average of 51% across the 48 locations. Examining the water and nitrogen budgets predicted by both models under FD and CD scenarios should explain why the two models differed substantially in predicting CD performance across the Midwest.

DRAINMOD and RZWQM predictions of annual drainage flow closely matched under FD scenario (Fig. 3a). Paired two sample *t*-test indicated that the differences between drainage flow predictions of the two models were statistically insignificant ($P = 0.3807 > 0.05$). On average across the 48 locations, drainage flow predictions of DRAINMOD and RZWQM were 27.9 and 28.3 cm yr^{-1}, respectively. Under this scenario both models predicted a small contribution of the surface runoff to the water balance; DRAINMOD predicted 3.9 cm yr^{-1} and RZWQM predicted

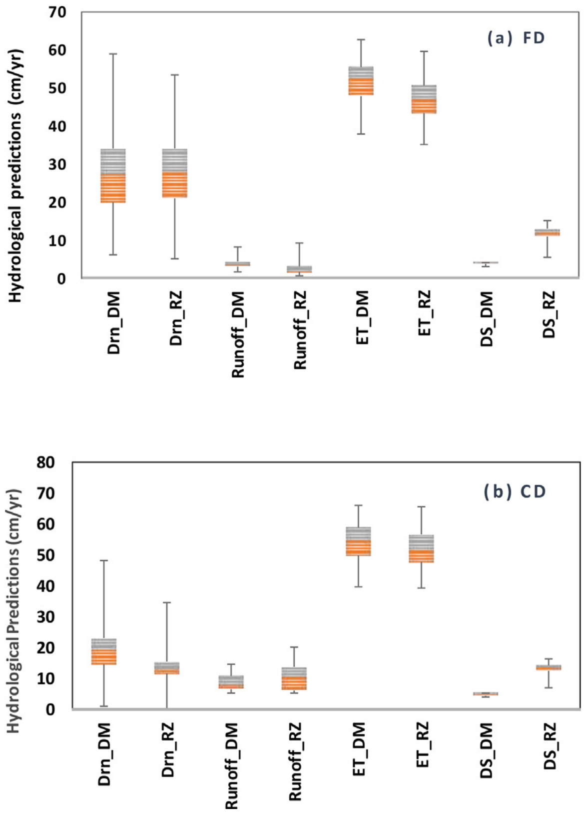


Fig. 4. Box plots comparing the hydrological predictions of DRAINMOD and RZWQM-DSSAT under free drainage (a) and controlled drainage (b) scenarios. Drn_DM, Runoff_DM, ET_DM, and DS_DM are average annual drainage flow, surface runoff, evapotranspiration, and deep seepage predicted by DRAINMOD, respectively. Drn_RZ, Runoff_RZ, ET_RZ, and DS_RZ are average annual drainage flow, surface runoff, evapotranspiration, and deep seepage predicted by RZWQM, respectively.

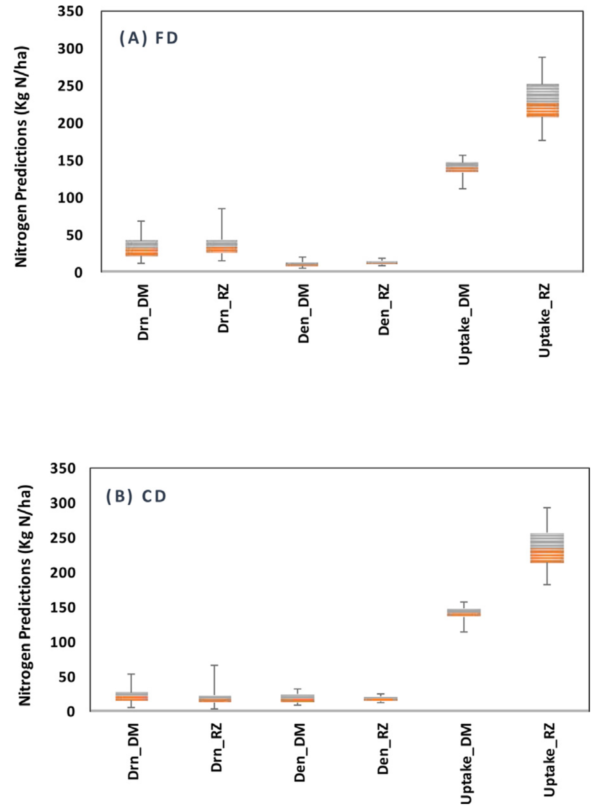


Fig. 5. Box plots comparing the nitrogen predictions of DRAINMOD-NII and RZWQM-DSSAT under free drainage (A) and controlled drainage (B) scenarios. Drn_DM, Den_DM, and Uptake_DM are average annual N loss via subsurface drainage, denitrification, and N uptake predicted by DRAINMOD, respectively. Drn_RZ, Den_RZ, and Uptake_RZ are average annual N loss via subsurface drainage, denitrification, and N uptake predicted by RZWQM-DSSAT, respectively.

2.6 cm yr^{-1}. However, ET and deep seepage predictions of the two models were quite different. DRAINMOD predicted average annual ET of 51.9 cm and deep seepage of 3.9 cm. RZWQM predicted less ET (46.8 cm yr^{-1}) and about three times more seepage (11.6 cm yr^{-1}) than DRAINMOD. Not only were seepage predictions by RZWQM much higher but also they exhibited much larger variation across locations than DRAINMOD predictions (Fig. 4a).

Under CD scenario, RZWQM consistently predicted much less drainage than DRAINMOD (Fig. 3b), which led to predicting much larger reductions in drainage flow (Fig. 3c). This is supported by the results of the *t*-test, which indicates a statistically significant difference ($P < 0.001$) between the drainage flows predicted by the two models under CD scenario. This is primarily because of differences in model predictions of surface runoff and ET. On average across the 48 locations, RZWQM predicted that CD increased surface runoff by 8.5 cm yr^{-1} (from 2.6 cm yr^{-1} to 11.1 cm yr^{-1}). On the other hand, DRAINMOD predicted that CD would increase surface runoff by only 4.8 cm yr^{-1} (from 3.9 cm yr^{-1} to 8.7 cm yr^{-1}). These differences in the simulated CD impact on surface runoff are mainly attributed to the fact that the former model does consider ponded conditions or surface storage. Fig. 3b shows that the deviation between drainage flow predictions by the two models under CD scenario become more pronounced as the drainage flow increases. Under CD scenario, relatively high drainage flow is most likely accompanied by high water table depth and surface runoff. Since RZWQM does not represent surface storage, this model is expected to over-predict surface runoff and under-predicted subsurface drainage under these conditions.

Evapotranspiration predictions by the two models for FD and CD scenarios were somewhat different presumably due to different approaches implemented in each model to simulate ET. On average across the 48 locations, DRAINMOD predicted 2.7 cm increase in ET, compared to 5.2 cm higher ET predicted by RZWQM. Despite the substantial difference in annual vertical seepage predicted by the two models for FD, both models predicted that CD would increase vertical seepage by only 1–1.5 cm yr^{-1}. According to these predictions, CD does not substantially increase vertical seepage for the soil and boundary conditions considered in this simulation study. However, the effect of CD on seepage may be considerable for other soils (Skaggs et al., 2010). The box plot shown in Fig. 4b visually compares the different components of the water balance predicted by the two models under CD scenario.

Similar to annual drainage predictions, RZWQM-DSSAT predicted larger reductions in annual N loss associated with CD, compared to DRAINMOD-NII predictions (Fig. 3f). Unlike drainage predictions; however, these larger reductions where caused by differences in model predictions of N losses under both FD and CD scenarios. This is supported by the results of the paired two sample *t*-tests showing that N drainage losses predicted by the two models were statistically significantly different under both FD ($P < 0.001$) and CD ($P < 0.001$) scenarios. RZWQM-DSSAT predicted higher N losses under FD scenario (Fig. 3d) and lower losses under CD scenario (Fig. 3e). RZWQM-DSSAT predicted substantially higher plant uptake than DRAINMOD-NII (90 kg N ha^{-1}yr^{-1} under FD and 94 kg N ha^{-1}yr^{-1} under CD) (Fig. 5), which is consistent with the results of Thorp et al. (2008), who stated that the overestimated N removal in corn grain predictions of RZWQM-DSSAT is one of the issues that limited the reliability of its crop growth simulations. Compared with RZWQM-DSSAT, DRAINMOD-NII predicted that CD would increase denitrification at relatively higher rates. DRAINMOD-NII predicted that implementation of CD would increase denitrification from 11 kg N ha^{-1} to 19 kg N ha^{-1}. According to RZWQM-DSSAT predictions, the implementation of CD would increase denitrification from 13 kg N ha^{-1} to 18 kg N ha^{-1}. Additionally, the discrepancies in predicted nitrogen loadings were also driven by the discrepancies in drain flow predictions.

4. Conclusion

The field scale hydrologic models, DRAINMOD and DRAINMOD-NII were used to simulate the effect of CD on the hydrology and N dynamics for 48 sites across Midwestern United States. The average reduction in subsurface drainage was 29.4% and the average reduction in N drainage losses was 32.3% across the region. The results indicated that the effect of CD on hydrology and nitrogen losses to surface waters differed spatially within the region. The minimum effect of CD on both hydrology and N losses was 1.4 cm yr^{-1}(23%) reduction in subsurface drainage flow and 1.5 kg N $ha^{-1}yr^{-1}$ (12.4%) reduction in N losses in drainage water occurred at the most northern site (Fargo, ND). The maximum effect occurred at the most southern site (Memphis, TN) where predicted subsurface drainage was reduced by 26.7 cm yr^{-1} (45.3%) and N loss via drainage water by 31.8 kg N $ha^{-1}yr^{-1}$ (46.8%). The predicted large reductions in drainage flow at the southern sites were accompanied by relatively large increase in surface runoff, which could lead to soil erosion and transport of sediment and phosphorus to receiving streams. Thus, care should be taken when managing the drainage control structures at sites that are prone to soil erosion. The results of DRAINMOD were compared to the results obtained by RZWQM (Thorp et al., 2008) for the same sites under the same conditions. Although, effects of CD on both drainage volumes and N losses predicted by RZWQM were larger than those predicted by DRAINMOD, the two models predicted similar trends across the region. The differences in predictions of DRAINMOD/DRAINMOD-NII and RZWQM-DSSAT are attributed to structural differences in both models, which differed in representing some of the key processes affecting the hydrology and N dynamics, including ET, surface runoff, denitrification, and N uptake. The results of this study can be used to inform policy makers, government agencies, and other stakeholders on where the practice can be implemented and what would be the expected long-term performance of implementing the practice at a specific geographic location within the U.S. Midwest region.

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