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Projected climate change effects on subsurface drainage and the performance of controlled drainage in the Western Lake Erie Basin

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Abstract: The US Midwest is expected to experience higher intensity rainfall events along with an increased chance of drought during the mid- and late 21st century under projected future climate scenarios. Development of strategies to mitigate the impact of these projected changes on agricultural production and environmental quality is important for ensuring agricultural resiliency to future climate. This study used the DRAINMOD hydrologic model to simulate subsurface drainage discharge at a field site in the headwaters of the Western Lake Erie Basin using future climate patterns projected by 20 general circulation models. Despite projected increases in rainfall, by the late twenty-first century, subsurface discharge was projected to decrease 7% and 11% under representative concentration pathway (RCP) 4.5 and RCP 8.5, respectively. Reductions in subsurface discharge were attributed to increased temperature and evapotranspiration. The performance of controlled drainage was not projected to change on an annual basis throughout the next century. The benefits of controlled drainage systems as an agricultural best management practice were still evident under the projected climate change of the next century. The role of controlled drainage as a means to potentially retain more crop available water in the soil profile could become critically important under future climate conditions.

Key words: climate modeling—drainage water management—DRAINMOD—Ohio

Evaluation of current agricultural best management practices, such as controlled drainage, under anticipated climate conditions is necessary to build resilient agricultural systems for the future. Projected changes in the global water balance under climate change will challenge agriculture to meet the demand for increased production to support a growing world population (IPCC 2013; Hatfield et al. 2011). The midwestern United States is an important agricultural region within the United States and is globally producing 10 billion bushels of corn (*Zea mays*) and 3 billion bushels of soybeans (*Glycine max* L.) annually (Niyogi and Mishra 2012). Under climate change, the Midwest is projected to experience higher-intensity rainfall events and increased spring rainfall (Pryor et al. 2014). Many agricultural soils in the Midwest are poorly and very poorly drained, leading to the implementation and intensification of subsurface drainage systems as a normal agricultural production practice (Fausey et al. 1995). Controlled drainage, also commonly referred to as drainage water management, is a currently recommended agricultural water management practice to reduce subsurface drainage discharge and soluble nutrient loads from the agricultural landscape within the Western Lake Erie Basin (Lake Erie Phosphorus Task Force 2010). While subsurface drainage is a critical component of the agricultural water balance in the Midwest, knowledge about the impacts of future climate change on subsurface hydrology and the performance of controlled drainage is limited. Understanding the impact of climate change on the amount and seasonal distribution of subsurface drainage is critical for determining future strategies to preserve agricultural production and environmental quality.

The Western Lake Erie Basin is one of the most extensively drained watersheds of the Midwest (Jaynes and James 2007; Ohio Lake Erie Phosphorus Task Force 2010). While removal of excess water from the soil profile is beneficial for agricultural production, an unintended consequence of subsurface discharge is the delivery of soluble nutrients from agricultural fields to surface waters. Controlled drainage uses an outlet control structure to artificially raise the elevation of the subsurface drainage outlet during periods when drainage is not needed for soil aeration or in-field operations. The primary benefit of controlled drainage for nutrient load reduction is related to its ability to reduce subsurface discharge. Several studies have reported that controlled drainage does not substantially change nitrate (NO_3) or soluble phosphorus (P) concentrations and found nutrient load reduction to be similar in magnitude to discharge reduction (Williams et al. 2015; Adeuya et al. 2012; Helmers et al. 2012; Jaynes 2012; Wesström and Messing 2007).

Future climate change is not expected to be uniform across regions. Changes in the water balance will depend on local changes in temperature and precipitation (IPCC 2013). For example, Ohio is projected to experience a greater increase in temperature and greater difference in the number of days with heavy precipitation than Iowa by midcentury (Pryor 2014). Singh et al. (2009) and Wang et al. (2015) projected that future climate would increase subsurface drainage discharge in Iowa, but differences in rainfall and temperature between Ohio and Iowa could affect subsurface drainage discharge differently in these two states. To determine how climate change will impact subsurface drainage discharge within the Western Lake Erie Basin, it is necessary to evaluate the water balance with localized climate projections.

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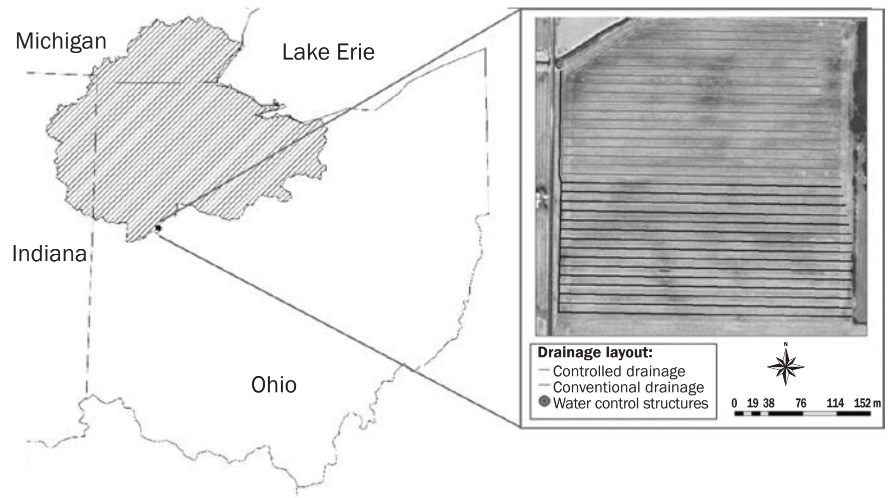
This study simulated subsurface drainage discharge and the performance of controlled drainage in the Western Lake Erie Basin using the DRAINMOD computer model during midcentury (2041 to 2070) and late-century (2071 to 2098) periods using an equal weighting Multimodel Ensemble (MME) approach under two future climate scenarios. The MME approach is well accepted for synthesizing the results from multiple general circulation models (GCMs) and was used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) to assess changes in the global water balance and mean surface temperatures relative to the historical period (Weigel et al. 2010; Flato et al. 2013; IPCC 2013).

Agricultural resiliency to climate change requires an understanding of how changes will impact current management practices. The objectives of this study were (1) to identify how future changes in rainfall and temperature will alter seasonal and annual subsurface drainage and (2) to evaluate the performance of controlled drainage as an agricultural best management practice under future climate conditions. Change in subsurface hydrology may indicate that change in drainage system design will be beneficial in the future. Change in the performance of controlled drainage systems may indicate that different management strategies will be required to enhance water quality and agricultural productivity.

Figure 1

Location of the field site within the Western Lake Erie Basin (hatched area) and the approximate site location (black square). Inset: drainage system layout.



Materials and Methods

To carry out this study, the following procedural steps were followed. Precipitation and subsurface drainage discharge were measured during a three-year study period at a field site in the Western Lake Erie Basin. These data, along with drainage system design and soil property information, were used to calibrate and validate the DRAINMOD model so that it could be used to estimate drain discharge under future climate scenarios. The future climate inputs that were used were synthesized using the MME procedure described by Tebaldi and Knutti (2007). These procedural steps are described more fully in the following sections.

Study Area and Observed Data. Observed data used for this study were collected from a privately owned field in Auglaize County, Ohio, from 2013 to 2015. The site is located in the headwaters of the Western Lake Erie Basin (figure 1). Soils at this site belong primarily to the Minster (fine, mixed, active, mesic Typic Endoaquolls) soil series with small areas of Blount (fine, illitic, mesic Aeric Epiaqualfs). These soils are classified as very poorly drained and have less than 1% slope on average.

The subsurface drainage system at this site has a drain spacing of 10 m (33 ft) at an approximate depth of 1 m (3.3 ft) below the soil surface. Two water control structures (WCS) (Agri Drain Corporation, Adair, Iowa) were installed in 2007 at the main drainage outlets for management of drainage system outlet elevation. The north portion of the field (7.16 ha [17.7 ac]) was managed with controlled drainage, and the south portion (7.28 ha [18 ac]) was left unmanaged to represent the conventional or freely drained condition.

Subsurface drainage discharge volume was determined by measuring the height of flow through and over a 7.6 cm (3 in) wide by 10.2 cm (4 in) deep v-notch weir cut into the topmost board in the WCS. Both controlled and conventionally drained WCS contained a v-notch weir board at all times. Water level upstream of the board setting was recorded at 15 minute intervals in each WCS using a Solinst Model 3001 Levelogger pressure transducer (Solinst Canada Ltd., Georgetown, Ontario, Canada). Manual readings were taken upstream of the boards to monitor drift in the recorded water levels. Flow height above the bottom of the v-notch weir was converted to flow rate using flow rating curves derived from an unpublished flow rating curve study as described by Gunn et al. (2015). "Conventional drainage" refers to the condition in which only a v-notch board was in place at the bottom of the WCS for discharge calculation purposes while "controlled drainage" refers to the condition in which one or more boards and a v-notch weir board were placed in the WCS to elevate the outlet. The adjustable boards in the WCS for the controlled drainage system were set to raise the drainage outlet when no crop was on the field and during the growing season. The outlet was set to conventional drainage levels prior to planting and harvest to assure field trafficability.

Rainfall was monitored using a TR-525I rainfall tipping bucket (Texas Electronics, Dallas, Texas). Field observations of rainfall were corrected to adjust for underestimation by the tipping bucket mechanism using the methodology described in Shedekar et al. (2016) for the TR-525 tipping bucket model. Missing rain gauge data were estimated on a daily basis using the Inverse Distance Weighting (IDW) method from available rainfall data recorded at locations within a 30 km (19 mi) radius of the field site (Ashraf et al. 1997). Rainfall observations for use with the IDW method were obtained from observed data at a nearby research site recorded by a Model 100 rainfall tipping bucket (Automata, Nevada City, California), and weather station data included in the National Oceanic and Atmospheric Administration National Climatic Data Center GHCN-Daily Database (Menne et al. 2012). Approximately 50% of the rainfall record from 2013 to 2015 required estimation using the IDW method.

Subsurface Drainage Discharge Modeling. Subsurface drainage discharge under future climate scenarios was simulated using DRAINMOD 6.1. DRAINMOD is a field-scale, process-based hydrologic model used to simulate water balance for high water table and artificially drained soils (Skaggs 1978). DRAINMOD uses climatological records and soil characteristics to simulate water balance at hourly and daily time scales (Skaggs et al. 2012).

DRAINMOD has been used to simulate performance of controlled drainage systems (Ale et al. 2009; Luo et al. 2010; Skaggs et al. 2010) and the effect of future climate scenarios on subsurface drainage systems and bioretention areas (Singh et al. 2009; Dayyani et al. 2012; Hathaway et al. 2014).

DRAINMOD Parameterization. Soil water retention and bulk density to a depth of 60 cm (24 in) were based on soil cores collected from the field site in 2011 and 2013 according to the standardized procedures and methodology agreed upon by the USDA National Institute of Food and Agriculture (NIFA) funded Climate and Corn-based Cropping Systems Coordinated Agricultural Project as described in Kladivko et al. (2014). These data were uploaded to a centralized database for review and quality control by data managers to ensure data integrity and adherence to standardization (Herzmann et al. 2014). Soil water retention and bulk density between 60 and 203 cm (24 to 80 in) in depth were obtained from estimates in the USDA Natural Resources Conservation Service (NRCS) Web Soil Survey. Saturated hydraulic conductivity was estimated from available soils data using the ROSETTA computer model (table 1). The ROSETTA model approximates soil pedotransfer hydrologic parameters using hierarchical neural network functions (Schaap et al. 1998). Other required DRAINMOD input parameters and their sources are listed in table 2.

Daily precipitation amounts were disaggregated on an hourly basis to fall within a four-hour time window starting at 10:00 AM EST using a routine within the DRAINMOD program. The starting time and duration of this window were based on the statistical probability of rainfall starting within a given hour and lasting for durations of 1 to 24 hours in observed hourly rainfall measurements recorded between 2011 and 2014 at this field site. Daily maximum and minimum temperature observations were obtained from the weather station at the Allen County Airport in Lima, Ohio, located approximately 22 km (14 mi) from the field location.

Evapotranspiration (ET) was simulated from temperature parameters using the Thornthwaite equation for estimated potential ET using the subroutine for monthly ET in the DRAINMOD model (Thornthwaite 1948). One limitation of this method is that the Thornthwaite method of estimating ET does not account for change in atmospheric carbon dioxide (CO_2) concentration. By the end of the century, atmospheric CO_2 is projected to rise to approximately 650 ppm CO_2 equivalent under RCP 4.5 and 1,370 ppm CO_2 equivalent under RCP 8.5 (Moss et al. 2008). Although rise in CO_2 equivalent is unaccounted for, prior studies have concluded that this will have minimal impact on the agricultural water balance (Field et al. 1995; Wang et al. 2015).

Evaluation of DRAINMOD Model Performance. Nash-Sutcliffe Modeling Efficiency (NSE) was used to evaluate subsurface discharge volume on a daily and monthly basis (Nash and Sutcliffe 1970), and percentage normalized error (PNE) was used to evaluate subsurface drainage discharge on an annual basis as recommended by Skaggs et al. (2012). NSE is a commonly used model calibration parameter for DRAINMOD (Youssef et al. 2006; Ale et al. 2009; Luo et al. 2010; Skaggs et al. 2012; Hathaway et al. 2014). Thresholds of model suitability using NSE and PNE were based on an assessment by Skaggs et al. (2012) of published studies that used in-field monitoring data to calibrate DRAINMOD. This assessment determined that for DRAINMOD, daily calibrations resulting in subsurface discharge with NSE > 0.4 were "acceptable," NSE > 0.60 were "good," and NSE > 0.75 were "excellent." Monthly calibrations resulting in subsurface discharge with NSE > 0.5 were "acceptable," NSE > 0.70 were "good," and NSE > 0.80 were "excellent." For annual subsurface discharge, PNE $< 25\%$ is "acceptable," PNE $< 15\%$ is "good," and PNE $< 5\%$ is "excellent."

Skaggs et al. (2012) recommends at least one year of data be used for calibration. Approximately three years of data (January 1, 2013, to November 20, 2015) were available for model calibration and validation for this study. Soil properties were generally consistent between the conventional drainage half of the field and the controlled drainage half of the field, so measurements from both drainage systems were used for model evaluation. Subsurface drainage discharge from the conventional drainage treatment from 2013 to 2015 were used in model calibration while subsurface drainage discharge and WCS board settings from the controlled drainage treatment from 2013 to 2015 were used in model validation. Daily, monthly, and annual statistics indicate that the model provided a reasonable fit for both the conventional and controlled drainage systems (table 3).

Model Adjustments for Future Climate Runs. For future climate simulations, weir settings for simulating controlled drainage management within DRAINMOD were based on recommended management guidelines for Ohio (Fausey 2016). Weir boards were set to 30 cm (12 in) below the ground surface for the nongrowing season (October 21 to April 1) and 46 cm (18 in) below the ground surface during the growing season (June 15 to September 21). Weir depth was set to drain depth to represent a "freely drained" condition during windows for planting and early crop establishment (April 1 to June 15) and harvest (September 21 to October 21).

Projections of Future Rainfall and Temperature. Future climate projections are informed by the amount of radiative forcing projected through the end of the 21st century (Moss et al. 2010). Radiative forcing indicates the difference in the amount of sunlight that is absorbed by the Earth's surface and atmosphere instead of radiated back to space and is influenced by concentrations of greenhouse gasses (GHGs) in the atmosphere. This study examines changes in subsurface drainage discharge patterns under two future radiative forcing scenarios known as representative concentration pathways (RCPs). RCPs were adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report to cover a range of radiative forcing levels resulting from projected changes in socioeconomic factors and GHG emissions through the end of the 21st century (Moss et al. 2010). RCP 4.5 represents a climate scenario in which global population stabilizes at 9 billion, and global emissions reduction policies lead to a peak in GHG emissions by 2050 with a decline to stable levels by 2080. Under this scenario, radiative forcing stabilizes at 4.5 W m^{-2} (1.2 Btu h^{-1} ft^{-2}) above preindustrial levels in 2100 (Thomson et al. 2011). RCP 8.5 represents a "business

Table 1
Soil physical properties used as ROSETTA model inputs.

Depth (cm)	Soil texture: Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Volumetric water content: −0.33 bar (cm^3 cm^{-3})	−15 bar (cm^3 cm^{-3})	Data source
0 to 10	8.0	52.4	39.6	1.48	0.37	0.24	Experimental
10 to 20	10.4	44.3	45.3	1.48	0.35	0.26	Experimental
20 to 40	7.4	47.3	45.3	1.53	0.36	0.26	Experimental
40 to 60	4.7	49.8	45.5	1.56	0.37	0.32	Experimental
60 to 83	5.8	49.4	44.8	1.92	0.34	0.27	NRCS web soil survey
83 to 91	6.4	49.3	44.3	1.94	0.33	0.28	NRCS web soil survey
91 to 99	9.2	49.3	41.5	1.87	0.32	0.25	NRCS web soil survey
99 to 142	9.0	49.6	41.4	1.87	0.31	0.24	NRCS web soil survey
142 to 203	6.2	52.4	41.4	1.85	0.29	0.21	NRCS web soil survey

Note: NRCS = USDA Natural Resources Conservation Service.

as usual" climate scenario in which global population increases to 12 billion by 2100 with no significant global climate policies to reduce GHG emissions. This is the highest GHG emissions scenario with radiative forcing increasing to 8.5 W m^{-2} (2.7 Btu h^{-1} ft^{-2}) above preindustrial levels in 2100 (Riahi et al. 2011).

All of the available GCMs from Phase Five of the Coupled Model Intercomparison Project (CMIP5) that had been downscaled for the contiguous United States were employed (table 4). Downscaled projections were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ (Maurer et al. 2007). Projections were bias-corrected and statistically downscaled to a daily time scale and to 1/8° spatial resolution (about 140 km^2 [54 mi^2] per grid cell) using the Bias-Correction Constructed Analogues (BCCA) method (Bureau of Reclamation 2013). The grid cell used in this study was centered at 40°33´45″ N, 84°3´45″ W. Using this method, 19 and 20 GCMs were available for RCP 4.5 and 8.5, respectively. CanESM2, CCSM4, CSIRO-Mk3.6.0, IPSL-CM5A-LR, MIROC5, MPI-ESM-LR, and MPI-ESM-MR (for RCP 4.5 only) had multiple members representing internal model variability due to different initial time conditions (table 4). Altogether, 83 climate projections were utilized as inputs for DRAINMOD simulations. Prior to analysis, daily precipitation data from the GCMs were disaggregated on an hourly basis in the same way as field-observed data. The results of the DRAINMOD simulations were synthesized using the equal weighting MME approach (Robertson et al. 2004; Tebaldi and Knutti 2007; Weigel et al. 2010; Flato et al. 2013). The equal weighting MME approach is a simple average of the results from multiple GCMs to represent the "best guess" for future projections (Tebaldi and Knutti 2007). In future climate studies, the term MME refers to a collection of simulations from different GCMs (Tebaldi and Knutti 2007; Flato et al. 2013). Use of a MME provides a more robust future projection than the use of a single GCM (Robertson et al. 2004; Weigel et al. 2010). In this study, seven GCMs had multiple members. In these cases, simulation results from all members of the GCM were averaged prior to calculating the MME mean to preserve equal weighting.

MME means over a 30-year period were used to evaluate changes in rainfall, temperature, and subsurface drainage discharge between the historical period (1971 to 2000), midcentury (2041 to 2070), and late-century (2071 to 2098). For rainfall and subsurface discharge, daily totals were summed on both an annual and monthly basis, then averaged over the 30-year period. For minimum and maximum temperature, daily high and low temperatures were averaged on a monthly and annual basis, and then were averaged over the 30-year period.

Statistical Analysis. All statistical analyses were performed in JMP 11.0 (SAS Institute 2013) at $\alpha < 0.05$. Comparisons between controlled and conventional drainage at the study site from 2013 to 2015 were conducted on a daily, monthly, and seasonal basis using *t*-tests. Daily subsurface discharge was tested with a *t*-test on days without management to compare baseline differences between the two drainage systems. Analyses of statistical significance between historical, midcentury, and late-century time periods were conducted using ANOVA and the Tukey-Kramer honest significant difference (HSD) test (Tukey 1953; Kramer 1956).

Results and Discussion

Observed Subsurface Drainage Discharge: 2013 to 2015. Under current climate conditions, controlled drainage reduces subsurface drainage discharge. During the study period, annual observed discharge was reduced between 16% and 24% on an annual basis (table 5). When the controlled drainage outlet was set to drain depth, there was no difference in outlet elevation between controlled drainage and conventional drainage. This condition occurred on a total of 453 monitored days during the three-year study period. During unmanaged periods, no statistically significant difference was observed in daily subsurface drainage discharge between controlled and conventional drainage systems. During managed periods (total of 569 monitored days), daily subsurface discharge from the controlled drainage system was significantly lower than from the conventional drainage system. Observed mean monthly discharge from 2013 to 2015 was 3.1 cm (1.2 in) for controlled drainage and 4.3 cm (1.7 in) for conventional drainage for a statistically significant mean monthly reduction of 1.3 cm (0.5 in). Controlled drainage management resulted in significant seasonal reductions in subsurface discharge during winter (January, February, and March) and summer (July, August, and September). No significant differences between controlled and conventional discharge were observed

Table 2
Input parameters for DRAINMOD.

Parameter	Value	Unit	Source
Drainage system design			
Depth to drains from soil surface	114	cm	Drainage system design and calibration
Spacing between drains	1,000	cm	Drainage system design
Effective radius of drains	0.51	cm	Drainage system design; Skaggs (1980)
Distance to impermeable layer	203	cm	NRCS web soil survey
Drainage coefficient	1.27	cm	Drainage system design
Maximum surface storage	2	cm	Calibration
Kirkham's depth for flow to drains	1	cm	Workman and Fausey (1985)
Lateral seepage			
Thickness of transmissive layer	100	cm	Calibration
Hydraulic head of receiving waters	30	cm	Calibration
Distance to receiving waters	19,000	cm	Distance to stream
Horizontal hydraulic conductivity of transmissive layer	0.001	cm h^{-1}	Calibration
Lateral saturated hydraulic conductivity			
Bottom depth of layer			
10 cm	7.23	cm h^{-1}	ROSETTA model output
20 cm	3.68	cm h^{-1}	ROSETTA model output
40 cm	4.80	cm h^{-1}	ROSETTA model output
60 cm	3.89	cm h^{-1}	ROSETTA model output
83 cm	1.04	cm h^{-1}	ROSETTA model output
Soil temperature			
Thermal conductivity function coefficients	a = 0.39; b = 1.33		DRAINMOD default value
Average air temperature below which precipitation is snow	−2	°C	Calibration
Average air temperature above which snow starts to melt	0	°C	Calibration
Snow melt coefficient	5	mm dd^{-1}	Calibration
Critical ice content above which infiltration stops	0.6	cm^3 cm^{-3}	Calibration
Phase lag for daily air temperature sine wave	8	hour	DRAINMOD default value
Soil temperature at the bottom of the profile	9.11	°C	DRAINMOD default value
Crop			
Lower limit of water content in the root zone	0.08	cm^3 cm^{-3}	DRAINMOD default value
Limiting water table depth	30	cm	DRAINMOD default value
Root depths (by date)			
May 5	3	cm	Skaggs (1980) and calibration
June 20	20	cm	Skaggs (1980) and calibration
July 18	45	cm	Skaggs (1980) and calibration
Aug. 30	80	cm	Skaggs (1980) and calibration
Sept. 30	80	cm	Skaggs (1980) and calibration
Oct. 20	3	cm	Skaggs (1980) and calibration
Trafficability			
Minimum air volume required to work the land	2	cm	Nolte et al. (1983)
Minimum rain to delay work	0.5	cm	Nolte et al. (1983)
Delay after rain to restart work	1	d	Nolte et al. (1983)
First work period			
Start date	Apr. 10		Barker et al. (2005)
End date	June 15		Barker et al. (2005)
Second work period			
Start date	Oct. 1		Barker et al. (2005)
End date	Dec. 31		Barker et al. (2005)

Table 3
Calibration and validation results for parameterization of the DRAINMOD model to the study site in Auglaize County, Ohio, from 2013 to 2015, using criteria of model performance as described in Skaggs et al. (2012).

Data set	Drainage system	Daily NSE*		Monthly NSE		Annual PNE†	
		Value	Criteria	Value	Criteria	Value	Criteria
Calibration:	Conventional	0.38	Acceptable	0.67	Acceptable	–10%	Good
Validation:	Controlled	0.37	Acceptable	0.75	Good	1.4%	Excellent

*NSE = Nash-Sutcliffe Efficiency as defined in Nash and Sutcliffe (1970).

†PNE = Percent Normalized Error as defined in Youssef et al. (2006).

during spring (April, May, and June) or autumn (October, November, and December).

These results were consistent with the findings of other controlled drainage studies in Ohio. Williams et al. (2015) found 8% to 34% annual reductions in annual subsurface discharge through use of controlled drainage management during an eight-year study period in an Ohio headwater watershed. Within the Western Lake Erie Basin, Gunn et al. (2015) found that controlled drainage reduced daily subsurface drainage discharge by 40% to 100% during managed periods.

Projected Changes in Temperature and Precipitation under Future Climate Conditions. All CMIP5 GCMs projected an increase in mean daily temperature throughout the next century (table 6). Under RCP 4.5 mean daily high and low temperatures were projected to stabilize around 2040 while under RCP 8.5 mean daily high and low temperatures were projected to increase through 2098 (table 7). MME mean daily high temperatures for the midcentury period increased 2.6°C (4.7°F) under RCP 4.5 and 3.4°C (6.1°F) under RCP 8.5 above

Table 4
Coupled Model Intercomparison Project Phase 5 general circulation models and modeling groups included in this study.

Model name	Model center (or group)	Ensemble members
ACCESS1.3	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	RCP* 4.5 - r1i1p1†, RCP 8.5 - r1i1p1
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
CanESM2	Canadian Centre for Climate Modelling and Analysis	RCP 4.5 - r[1-5]i1p1, RCP 8.5 - r[1-5]i1p1
CCSM4	National Center for Atmospheric Research	RCP 4.5 - r[1-2]i1p1, RCP 8.5 - r[1-2]i1p1
CESM1(CAM5)	Community Earth System Model Contributors	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
CNRM-CM5	Centre National de Recherches Météorolgiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) in collaboration with Queensland Climate Change Centre of Excellence	RCP 4.5 - r[1-10]i1p1, RCP 8.5 - r[1-10]i1p1
GFDL-CM3	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory	RCP 8.5 - r1i1p1
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
INM-CM4	Institute for Numerical Mathematics	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
IPSL-CM5A-LR	Institute Pierre-Simon Laplace	RCP 4.5 - r[1-4]i1p1, RCP 8.5 - r[1-4]i1p1
IPSL-CM5A-MR	Institute Pierre-Simon Laplace	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	RCP 4.5 - r[1-3]i1p1, RCP 8.5 - r[1-3]i1p1
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
MPI-ESM-LR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	RCP 4.5 - r[1-3]i1p1, RCP 8.5 - r[1-3]i1p1
MPI-ESM-MR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	RCP 4.5 - r[1-3]i1p1, RCP 8.5 - r1i1p1
MRI-CGCM3	Meteorological Research Institute	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1
NorESM-M	Norwegian Climate Centre	RCP 4.5 - r1i1p1, RCP 8.5 - r1i1p1

*RCP indicates the representative concentration pathway simulated for each climate model.

†Ensemble members are represented using: *r* < N > *i* < M > *p* < L > format where *r* is the initial condition (time), *i* is the initialization method, and *p* is the perturbed physics ensemble (Taylor et al. 2009).

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Table 5
Observed subsurface discharge from conventional and controlled drainage systems at the study site in Auglaize County, Ohio, from 2013 to 2015.

	Year		
Drainage system	2013	2014	2015
Conventional (cm)	45	41	66
Controlled (cm)	34	33	56
Reduction (%)	24	20	16

the average from the historical period (table 6). MME mean daily high temperatures during the late-century period increased by an average of 3°C (5.4°F) under RCP 4.5 and 5.4°C (9.7°F) under RCP 8.5 (table 7). MME mean daily low temperatures exhibited a similar trend to daily high temperatures (table 7). Significant increases in temperature over the historical period were projected during the midcentury period and the late-century period in every season for both RCP 4.5 and RCP 8.5 (table 8).

There was high agreement among CMIP5 GCMs that annual precipitation would increase under both scenarios for the midcentury and late-century periods (table 6). Greater increases in annual precipitation were projected for RCP 4.5 than for RCP 8.5 (table 7). By midcentury, annual precipitation was projected to increase 4.4% under RCP 4.5 and 3.4% under RCP 8.5 (table 7). By late-century, annual precipitation was projected to increase 5.3% under RCP 4.5 and 5% under RCP 8.5 (table 7). Seasonal precipitation was projected to increase significantly compared to the historical period during winter, spring, and autumn under both RCP 4.5 and 8.5 (table 8). No significant differences from the historical period were observed during summer. Under RCP 8.5, precipitation was projected to increase significantly from the midcentury period to the late-century period during winter, but not during other seasons.

Projected Changes in Conventional Subsurface Drainage Discharge under Future Climate Conditions. Using CMIP5 GCMs to drive DRAINMOD simulations revealed that conventional subsurface drainage discharge is likely to decrease in the Western Lake Erie Basin throughout the next century (table 6). A greater decline in discharge was projected for RCP 8.5 than for RCP 4.5. For RCP 4.5, projected subsurface discharge decreased 12.3% by midcentury and 14.5% by late-century (table 7). For RCP 8.5, projected subsurface discharge decreased 14.3% by midcentury and 23.7% by late-century (table 7). The annual decrease in subsurface discharge was statistically significant between the historical period and midcentury period for RCP 4.5 (table 9). The decrease in subsurface discharge from midcentury to late-century was statistically significant for RCP 8.5 (table 9).

Seasonal subsurface drainage discharge in conventional drainage systems was greatest in winter and lowest in summer under both historical and future climate conditions (table 9). This trend was consistent with the findings of King et al. (2014) for conventional subsurface discharge in an Ohio headwater watershed. The greatest decline in subsurface drainage discharge under future climate conditions was projected to occur during autumn. Under RCP 4.5 depth of subsurface drainage discharge was projected to significantly decrease by an average of 9 mm (0.4 in) during winter, 7 mm (0.3 in) during spring, 9 mm (0.4 in) during summer, and 22 mm (0.9 in) during autumn by midcentury (table 9). Under RCP 4.5, seasonal subsurface discharge was not projected to change significantly from the midcentury period to the late-century period (table 9). Under RCP 8.5, subsurface drainage discharge was projected to decrease by an average of 8, 9, and 30 mm (0.3, 0.4, and 1.2 in) during spring, summer, and autumn, respectively, by midcentury (table 9). Subsurface drainage discharge during winter was not significantly different between the historical and midcentury periods (table 9). Significant decreases in subsurface drainage discharge between the midcentury and late-century periods were projected during winter, summer, and autumn under RCP 8.5 (table 9).

The decrease in annual subsurface discharge found in this study differs from the findings of Singh et al. (2009) and Dayyani et al. (2012), which found overall increases in annual subsurface drainage discharge in Iowa, United States, and Quebec, Canada, respectively. The difference in response to future climate change could be a result of the existing differences in regional hydrology between Ohio and more northern areas of the Midwest and Canada. Under current climate conditions, Ohio soils do not freeze for significant lengths of time during winter. In areas without frozen winter soils, subsurface drainage discharge tends to be greatest from the late fall to the early spring (Randall and Goss 2001). In more northern areas of the Midwest like Iowa, Minnesota,

Table 6
Number of individual general circulation models projecting an increase or decrease in annual precipitation and temperature, and via DRAINMOD simulation, projecting an increase or decrease in annual subsurface drainage discharge relative to the historical period (1971 to 2000) for an agricultural field representative of the Western Lake Erie Basin for two representative concentration pathways (RCPs).

		Midcentury (2041 to 2070)			Late-century (2071 to 2098)		
Variable	RCP	Increase	No change*	Decrease	Increase	No change*	Decrease
Daily maximum temperature (°C)	4.5	19	0	0	19	0	0
	8.5	20	0	0	20	0	0
Daily minimum temperature (°C)	4.5	19	0	0	19	0	0
	8.5	20	0	0	20	0	0
Precipitation (%)	4.5	16	2	1	15	1	3
	8.5	15	1	4	15	1	4
Conventional subsurface discharge (%)	4.5	2	1	16	2	0	17
	8.5	0	0	20	2	0	18

*Difference of less than 1% between the historical period and midcentury or late-century periods.

Table 7
Multimodel ensemble (MME) mean change in annual temperature and precipitation from general circulation model climate projections, and MME mean change in subsurface drainage discharge as simulated by DRAINMOD relative to the historical period (1971 to 2000) for an agricultural field representative of the Western Lake Erie Basin for two representative concentration pathways (RCPs).

	Midcentury (2041 to 2070)		Late-century (2071 to 2098)	
Variable	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Daily high temperature (°C)	+2.6	+3.4	+3.0	+5.4
Daily low temperature (°C)	+2.7	+3.5	+3.2	+5.4
Precipitation (%)	+4.4	+3.4	+5.3	+5.0
Conventional subsurface discharge (%)	−12.3	−14.3	−14.5	−23.7

and Quebec, frozen soils prevent subsurface drainage discharge from occurring during winter months (Randall and Goss 2001; Helmers et al. 2005; Eastman et al. 2010).

Increases in temperature due to climate change are likely to have a greater impact on the seasonal distribution of subsurface drainage areas with frozen winter soils than areas without frozen soils. Both Dayyani et al. (2012) and Singh et al. (2009) project the greatest increases in subsurface drainage discharge during winter and attribute this change to increasing winter temperatures under future climate conditions. Increased winter temperatures would result in less snow accumulation, shorter periods of frozen soil, and increased infiltration of water into the soil profile during winter months leading to increased subsurface drainage discharge (Dayyani et al. 2012; Singh et al. 2009). In Ohio, the increase in winter temperature due to future climate change will not increase infiltration of water into the soil profile. As a result, increases in subsurface drainage discharge in winter and the potential for a subsequent increase in soluble nutrient losses would not be as likely to occur in Ohio as in higher-latitude areas of the Midwest and Canada.

The difference in projected subsurface drainage discharge could also be a result of differences in future climate projections between Ohio, Iowa, and Quebec. Greater increases in average annual temperature coupled with lower average increases in annual precipitation were projected in this study compared to Singh et al. (2009) and Dayyani et al. (2012). Higher temperatures are projected to drive higher rates of ET from increased crop transpiration and soil evaporation (Hatfield et al. 2011). This effect, combined with lower increases in annual precipitation in Ohio compared to Iowa and Quebec, suggests that there may be lower soil moisture in the soil profile under future climate conditions reducing annual subsurface drainage discharge.

Performance of Controlled Drainage under Future Climate Conditions. The annual performance of controlled drainage systems was not projected to change as a result of changes in climate throughout the 21st century (table 10). Average annual percentage reductions in discharge did not change significantly over time and ranged between 4.3% and 6% for the three time periods examined in this study. This result demonstrates that the environmental benefits of controlled drainage (discharge and soluble nutrient reduction) will remain evident under future climate conditions.

Significant differences in the seasonal performance of controlled drainage systems were observed in summer and autumn. In summer, seasonal reductions in discharge through controlled drainage management were projected to increase significantly from 23.5% during the historical period to 39.6% during the midcentury period under RCP 4.5 and from 43.4% during the midcentury period to 81.8% during the late-century period under RCP 8.5.

The improved efficiency of controlled drainage during summer months reflects that use of controlled drainage during the growing season could become a critical component of water management under future climate conditions. With increased temperature driving increased ET, the potential for soil water deficits is increased (Hatfield et al. 2011). Reducing water loss through subsurface drains with controlled drainage management could help meet the crop water requirements in spite of increased ET. In addition, farmers are likely to invest in subsurface drainage systems in response to increased rainfall (Loy et al. 2013). In many

Table 8
Multimodel ensemble mean change in seasonal temperature and precipitation from the historical period (1971 to 2000) to the midcentury (2041 to 2070) and late-century periods (2071 to 2098) for an agricultural field representative of the Western Lake Erie Basin for two representative concentration pathways (RCPs).

		Low temperature (°C)		High temperature (°C)		Precipitation (mm)	
Season	RCP	Midcentury	Late-century	Midcentury	Late-century	Midcentury	Late-century
Winter	4.5	+2.8	+3.4	+2.5	+2.9	+17	+20
	8.5	+3.5	+5.3	+3.2	+4.8	+29	+40
Spring	4.5	+2.5	+3.1	+2.4	+2.9	+14	+15
	8.5	+3.3	+5.2	+3.2	+5.1	+16	+21
Summer	4.5	+2.8	+3.3	+2.8	+3.2	−1	+3
	8.5	+3.7	+5.8	+3.7	+5.9	+3	+4
Autumn	4.5	+2.6	+3.1	+2.5	+2.9	+11	+12
	8.5	+3.3	+5.2	+3.4	+5.3	+12	+15

Notes: Winter = January, February, and March. Spring = April, May, and June. Summer = July, August, and September. Autumn = October, November, and December.

Table 9

Multimodel ensemble mean seasonal and annual conventional subsurface discharge as projected by DRAINMOD simulation for an agricultural field representative of the Western Lake Erie Basin for two representative concentration pathways (RCPs).

		Conventional subsurface drainage discharge (mm)		
Season	RCP	Historical (1971 to 2000)	Midcentury (2041 to 2070)	Late-century (2071 to 2098)
Winter	4.5	158a*	149b	148b
	8.5	158a	152a	139b
Spring	4.5	125a	118b	116b
	8.5	125a	117b	112b
Summer	4.5	21a	12b	11b
	8.5	19a	10b	6c
Autumn	4.5	70a	48b	43b
	8.5	69a	39b	26c
Annual	4.5	373a	327b	319b
	8.5	371a	318b	283c

Notes: Winter = January, February, and March. Spring = April, May, and June. Summer = July, August, and September. Autumn = October, November, and December.

*Values in the same row indicated by a different lowercase letter are significantly different at $\alpha = 0.05$.

Table 10

Mean seasonal and annual reductions in subsurface drainage discharge through controlled drainage management as simulated by DRAINMOD for an agricultural field representative of the Western Lake Erie Basin for two representative concentration pathways (RCPs).

		Reduction in subsurface discharge with controlled drainage management (mm)		
Season	RCP	Historical (1971 to 2000)	Midcentury (2041 to 2070)	Late-century (2071 to 2098)
Winter	4.5	26.80	25.10	27.80
	8.5	26.80	24.30	26.60
Spring	4.5	−19.80	−19.30	−17.50
	8.5	−19.90	−18.10	−18.30
Summer	4.5	4.50	4.39	4.00
	8.5	4.41	2.94	3.73
Autumn	4.5	9.44	5.84	5.04
	8.5	9.29	2.64	4.46
Annual	4.5	20.90	16.00	19.30
	8.5	20.30	17.00	12.50

Notes: Winter = January, February, and March. Spring = April, May, and June. Summer = July, August, and September. Autumn = October, November, and December.

cases this means increasing subsurface drainage density in their fields to maintain spring planting efficiency. The increased potential for water loss due to increased drainage intensity will increase the value of reducing subsurface discharge during the growing season under future climate conditions. Reductions in subsurface drainage discharge through use of controlled drainage represent a potential increase in the available water in the soil profile for crop growth and a potential for increased production benefits through the use of controlled drainage.

Under RCP 8.5, controlled drainage was projected to be less effective at reducing subsurface drainage discharge in autumn during the late-century period compared to the historical period (table 10). Controlled drainage was projected to reduce winter discharge by 17% to 19% on average throughout the next century, but was projected to increase spring discharge by 16% to 18% on average (table 10).

The projected increase in spring subsurface discharge from controlled drainage systems reveals a discrepancy between the parameterized model and the observed data. The model projects that when the WCS is opened nearly all of the water held back through the winter period is released over a two to three day period in April. The release of water from the soil profile was more dramatic in the model simulation than in observed data at the study site. This discrepancy is also reflected through annual percentage reductions in subsurface discharge. The parameterized model predicted average annual reductions between 4% and 6%, while observed discharge reductions were between 16% and 24% annually during the study period. The difference between observed and simulated response to controlled drainage may result from the assumption that vertical seepage was negligible during model parameterization. This assumption was supported by model calibration and by a regional study on vertical seepage in western Ohio, which found saturated hydraulic conductivity through glacial till to be $1.11 \pm 0.556 \times 10^{-6}$ cm s^{-1} (0.002 ± 0.001 in hr^{-1}) (Fausey et al. 2000). Although the model provides a reasonable fit to the observed data, the discrepancy reveals that vertical seepage processes may not be adequately represented within the model. A prior DRAINMOD study by Skaggs et al. (2010) concluded that field experiments on controlled drainage were necessary to adequately represent the role of seepage in discharge reduction. While the DRAINMOD model may underestimate the role of seepage in discharge reduction, this limitation does not affect the conclusion of this study that the performance of controlled drainage will not change under future climate.

Although the increase in discharge due to lowering the board settings was overpredicted by the model, this result demonstrates a potential unintended outcome of controlled drainage management. This suggests that alternative strategies for spring management, such as draining the profile slowly instead of draining the entire soil profile at once, could be beneficial in reducing spring discharge and potential release of soluble nutrients from the soil profile. A slower lowering of the drainage outlet could encourage increased losses of water from the soil profile via other pathways (ET or seepage) rather than via the drainage outlet.

Summary and Conclusions

This study simulated the performance of subsurface drainage systems under future climate scenarios using the DRAINMOD hydrologic model. Climate change is expected to increase annual rainfall and temperatures in the Western Lake Erie Basin. Despite increases in projected rainfall, by midcentury subsurface drainage discharge was projected to decrease by 12.3% and 14.3% under RCP 4.5 and RCP 8.5, respectively. By the late 21st century, subsurface discharge is projected to decrease 14.5% under RCP 4.5 and 23.7% under RCP 8.5. By the late 21st century, subsurface drainage discharge was projected to significantly decline compared to the historical period in all seasons with the greatest discharge depth reduction occurring during the autumn.

This study demonstrates that the benefits of controlled drainage under current climate conditions will still be evident under projected future climate. The performance of controlled drainage on an annual basis was not projected to change under future conditions, so controlled drainage will remain an important practice for reducing subsurface drainage discharge and potential soluble nutrient losses under future climate conditions. By the late-century period, controlled drainage was projected to increase in efficiency during summer from a 23.5% to 24.6% reduction in subsurface drainage discharge under historical climate conditions to a 42.7% reduction for RCP 4.5 and an 81.8% reduction for RCP 8.5 under late-century climate conditions.

With warmer temperatures driving higher rates of ET, increasing soil water storage for potential use by the crop will become increasingly valuable during the growing season. Increases in discharge observed during the spring when the drainage outlet is lowered could indicate the need to more closely examine procedures for lowering the controlled drainage outlet prior to spring planting operations.

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