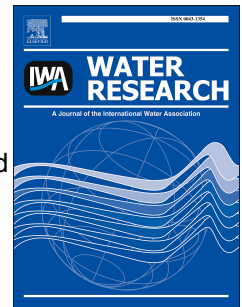


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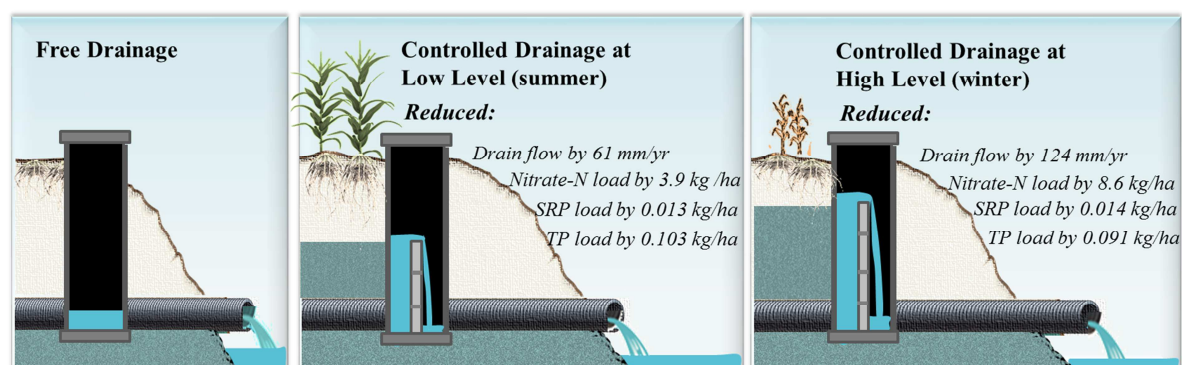
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Nitrate and Phosphorus Transport through Subsurface Drains under Free and Controlled Drainage

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ABSTRACT.

Controlled drainage (CD) is a structural conservation practice in
which the drainage outlet is managed in order to reduce drain flow
volume and nutrient loads to water bodies. The goal of this study
was to evaluate the potential of CD to improve water quality for
two different seasons and levels of outlet control, using ten years
of data collected from an agricultural drained field in eastern
Indiana with two sets of paired plots. The Rank Sum test was used
to quantify the impact of CD on cumulative annual drain flow and
nitrate-N and phosphorus loads. CD plots had a statistically
significant (at 5% level) lower annual drain flow (eastern pair:
39%; western pair: 25%) and nitrate load (eastern pair: 43%;
western pair: 26%) compared to free draining (FD) plots, while
annual soluble reactive phosphorus (SRP) and total phosphorus
(TP) loads were not significantly different. An ANCOVA model
was used to evaluate the impact of CD on daily drain flow, nitrate-

34 N, SRP and TP concentrations and loads during the two different
 35 periods of control. The average percent reduction of daily drain
 36 flow was 68% in the eastern pair and 58% in the western pair
 37 during controlled drainage at the higher outlet level (winter) and
 38 64% and 58% at the lower outlet level (summer) in the eastern and
 39 western pairs, respectively. Nitrate load reduction was similar to
 40 drain flow reduction, while the effect of CD on SRP and TP loads
 41 was not significant except for the increase in SRP in one pair.

42 These results from a decade-long field monitoring and two
 43 different statistical methods enhance our knowledge about water
 44 quality impacts of CD system and support this management
 45 practice as a reliable system for reducing nitrate loss through
 46 subsurface drains, mainly caused by flow reduction.

47
 48 **Keywords.**

49 Drainage water management, phosphorus, nitrate, ANCOVA, ARMA errors,
 50 subsurface drain
 51

52 **1. Introduction**

53 Subsurface drainage is a necessary water management practice
 54 in agricultural fields with naturally poorly drained soil, however, it
 55 contributes to water quality issues. Studies suggest that nitrate loss
 56 through subsurface drainage is the main source of nitrate in surface
 57 water (David et al., 1997; Jaynes and Colvin, 2006) and a leading
 58 cause of hypoxia in regions such as the northern Gulf of Mexico
 59 (Goolsby et al., 1999 and Rabalais et al., 2001). Phosphorus (P)

60 can also be transported through drainage systems in dissolved and
61 particulate forms (King et al., 2015) and preferential flow appears
62 to be a frequent mechanism of P transport into subsurface drains
63 (Stamm et al., 1998). Phosphorus loads through subsurface drains
64 are much lower than nitrate loads, which has led to less attention to
65 this loss pathway, but recent studies have shown the importance of
66 P lost through subsurface drainage (King et al., 2015; Kleinman et
67 al., 2015; Lam et al., 2016; Van Esbroeck et al., 2016). For
68 example, Smith et al. (2015) reported that 49% of soluble P and
69 48% of total P losses from fields in the St. Joseph River Watershed
70 in northeastern Indiana occurred via subsurface discharge.

71 Many approaches have been suggested in the literature to
72 mitigate water quality issues caused by subsurface drainage.
73 Among these, controlled drainage (CD) is a structural conservation
74 practice in which the drainage outlet is managed in order to reduce
75 drain flow volume and nutrient loads to water bodies. (Evans et al.,
76 1995; Fausey 2004; Frankenberger et al., 2006; Singh, et al., 2007;
77 Adeuya et al., 2012; Gunn et al., 2015; Williams et al., 2015a). A
78 comprehensive comparison between controlled and free draining
79 systems from 13 experimental field studies at 7 different locations
80 (USA: North Carolina, Ohio, Iowa, Indiana, Illinois; Canada:
81 Ontario; and Sweden) by Skaggs et al. (2012) indicated a broad
82 range of reductions from 18% to over 85% in average annual drain

83 flow and from 18% to 79% in annual nitrate loss via drainage
84 under CD. In some of these studies, denitrification has been found
85 to lower the nitrate-N concentrations in the subsurface outflow
86 when drainage was controlled (Kliewer and Gilliam, 1995 and Tan
87 et al., 1998). However, in most studies, the significant decrease in
88 nitrate loads has been shown to be a result of reduction in drain
89 flow rather than the reduction in nitrate-N concentrations (e.g.,
90 Westrom and Messing, 2007; Adeuya et al., 2012, Lavaire et al.,
91 2017).

92 From a synthesis analysis based on 17 measured field studies
93 and 11 modeled studies, Ross et al. (2016) found that CD reduced
94 annual drain flow by 46% and annual nitrate loads by 48%. Ross et
95 al. (2016) additionally reported a 57% reduction in soluble P loads
96 and a 55% reduction in total P loads with CD, based on only a few
97 studies available in the literature at that time. Nash et al. (2015)
98 found that CD decreased soluble P load in the subsurface flow by
99 80% in a claypan soil in Missouri due to both a decrease in soluble
100 P concentration and reduced drain flow.

101 Although field studies on the effect of CD on drain flow and
102 nitrate loss through subsurface drainage have been ongoing for
103 decades, most have been conducted for a period of less than 5
104 years. There is also variability in the performance of CD in the
105 literature and a wide range of changes in drain flow and nitrate

106 loads with CD has been reported from different experimental sites.
107 This suggests more studies are still required to provide a complete
108 understanding of nitrate and P transport from agricultural fields to
109 surface water bodies under different weather conditions, soil types,
110 cropping systems and drainage designs over a long-term period. In
111 addition to variability among sites, the design and statistical
112 analysis used to assess CD effects have also varied, which may add
113 to the apparent variability in results.

114 This paper reports results from a decade-long study in Indiana.
115 Having ten years of drain flow and nitrate-N concentrations and
116 five years of SRP and TP concentrations allows a statistical
117 analysis of the cumulative annual impact of CD, in addition to the
118 common paired field statistical analysis of daily values. This study
119 also includes P transport through subsurface drains. Unlike nitrate,
120 only a few studies have quantified the impacts of CD on P
121 concentrations and loads via subsurface drains. In addition, this
122 study evaluates the water quantity and quality impacts of CD
123 during winter (high outlet level control period) versus summer
124 (low outlet level control period), which has not been emphasized in
125 previous studies. The overall goal of this study was then to
126 evaluate the potential of CD to improve water quality, using ten
127 years of data collected from an agricultural drained field in eastern
128 Indiana. Specific objectives were to:

- 129 1- Assess the impact of CD on annual drain flow and nutrient
130 (nitrate-N, SRP and TP) loads;
- 131 2- Quantify the relative influence of changes in drain flow
132 versus changes in concentration on reductions in load due to
133 CD;
- 134 3- Evaluate the impact of CD during periods of high outlet
135 level control (winter) and low outlet level control (summer).

137 2. Materials and Methods

138 2.1.Site description

139 The controlled drainage experimental site for this study is field
140 W at Davis Purdue Agricultural Center (DPAC) located in eastern
141 Indiana. Field W is relatively flat (slope < 1%), with 0.16 km² (39-
142 acre) total area, divided into four plots, northwest (NW), southwest
143 (SW), northeast (NE), and southeast (SE) with areas ranging from
144 3.5 ha to 3.7 ha (Figure 1). The four soil series at the site range
145 from very poorly to somewhat poorly drained, with a small portion
146 of moderately well drained series. The subsurface drainage system
147 was installed in September 2004, with 10-cm (4 inch) laterals
148 having an approximate depth of 1 m and spacing of 14 m (Utt,
149 2010), resulting in a drainage intensity of 1.1 cm day⁻¹ and
150 drainage coefficient of 1 cm. Drainage in the SE and NW plots was
151 controlled at two different levels during some periods depending
152 on the season (Figure 2), while the SW and NE were allowed to

153 drain freely. This field has been in a corn-soybean rotation since
154 2011 and in continuous corn before that, and was managed using
155 chisel-plow tillage in the fall and field cultivator tillage in the
156 spring during the study period. Nitrogen (N) and phosphorus (P)
157 fertilizers were applied at different rates prior to and after planting
158 corn (Table 1). Phosphorus was also applied prior to soybean
159 planting in two of the three soybean years. The rate and timing of
160 fertilizer applications were uniform for all plots and were based on
161 Purdue Extension recommendations. Further details of the site
162 management and data are available in Abendroth et al. (2017).

163 **2.2.Operational strategy of controlled drainage**

164 Drainage was controlled at different levels during winter and
165 summer (non-growing and growing seasons). The drainage outlet
166 was raised to 10 cm below the ground surface after harvest,
167 sometime between November and December, remained at that
168 level through early to mid-April each year (winter, high-level) and
169 was lowered to the drain depth a few weeks before planting. The
170 outlet was raised to 40 cm below the ground surface after spring
171 fieldwork (late May to early June) through the end of September
172 (summer, low-level). This analysis distinguished the effects of CD
173 during higher-level control (HL) and lower-level control (LL). The
174 dates when the outlets were raised and lowered and the height to
175 which they were raised were similar in most years (Figure 2)

except for 2012 (drought) and 2015 (management error) when the drainage outlet was never lowered to the drain depth.

2.3.Drain flow measurements combined with estimations

Drain flow has been measured using electromagnetic flow meters (Krohne Waterflux 3070) since 2012. Prior to that, drain flow monitoring was unreliable but water table was more consistently measured using pressure transducers (Global Water WL-16) installed in observation wells located at the midpoint between two drains in each plot. Therefore, drain flow was estimated using the Hooghoudt equation and water table depth measurements for each hour for which water table measurement was available from January 2007 through December 2016, in a method described in Saadat et al. (2018). Estimated drain flow was combined with observations for the periods that drain flow was measured (2012 to 2016) in order to fill in the gaps. Due to missing values in the water table observations, gaps remained in the drain flow dataset, therefore, linear regression equations of the flow observations from one plot against a paired plot with the same treatment (free or controlled drainage) were used to fill the majority of the missing values (Saadat et al., 2018). After drain flow was filled using the methods explained above, small gaps (54 days over 10 years) still remained in the dataset when there was no measured water table depth or measured flow from the paired plot

(Figure 3). These gaps were mostly during the summertime when drain flow was relatively low compared to other times of the year, and days with missing drain flow were not included in the analysis.

2.4. Sampling and concentration interpolation method

Automated water samplers (ISCO) were used to draw samples from the drainage outlet flow of each plot, downstream of the control structure. Samples were collected every hour when flow was present except during winter, and combined into weekly composite samples varying in length from twice a week to biweekly. During the winter, water samples were collected manually to avoid freezing problems, approximately every week whenever flow was present. A total of 2130 samples were collected during the study period from which 355 were manually collected grab samples. Samples were kept frozen until analysis and then analyzed on a SEAL Analytical AQ2 auto-analyzer to be tested for nitrate+nitrite-N (referred to subsequently as nitrate-N), soluble reactive phosphorus (SRP) and total phosphorus (TP) according to US EPA methods.

Daily nitrate-N, SRP and TP concentration values needed for the load calculations were estimated using linear interpolation, because water quality samples were collected weekly or less frequently. The composite samples from the automated samplers were considered representative of all days since the previous sample was

collected. For manual samples collected in winter, daily concentration was calculated using linear interpolation between data points.

After estimating daily concentrations, daily loads were calculated by multiplying the daily drain flow by estimated daily concentrations.

2.5. Statistics and data analysis

In order to evaluate the effect of the CD system statistically, the two eastern and western plots were paired due to their similar water table recession characteristics, as was also done by Saadat et al. (2017). Two separate analyses were conducted with different purposes. The Rank Sum test was used for annual discharge and load, while daily discharge and load and weekly concentration were analyzed using ANCOVA.

2.5.1. Annual flow and loads using Rank Sum test

Annual drain flow and nutrient loads were determined by summing the daily flow and loads for each plot for each calendar year from 2007 to 2016 for drain flow and nitrate loads and from 2012 to 2016 for SRP and TP loads. The annual reduction in the CD plots was tested using the non-parametric Rank Sum test (Bradley, 1968). The magnitude of change for the Rank Sum test was estimated with the Hodges-Lehmann estimator (Hodges and Lehmann, 1963), which is the median of all possible paired differences between annual flow/load in the FD plots and CD

plots.

2.5.2. Daily/weekly values using ANCOVA test

The analysis of covariance (ANCOVA) was used to determine the impacts of CD on daily drain flow, daily nutrient loads and measured nutrient concentrations (approximately weekly). For this model, two fields (control and treated) and two periods (calibration and treatment) are required (Clausen and Spooner, 1993). In this study, the treatment period was further divided into two periods, higher-level (HL) control and lower-level (LL) control periods (Figure 2). Linear regression of the free-draining periods (calibration) was used to test the significance of the relationship between paired observations. If the relationship was significant, the regressions in the treatment period were tested to determine the significance of the difference between the calibration and treatment periods.

The general equation used for the ANCOVA model was:

$$Y = \beta_0 + \beta_1 X + \beta_2 Z_1 + \beta_3 Z_2 + \beta_4 Z_1 X + \beta_5 Z_2 X + e$$

where the dependent variable (Y) is daily drain flow or daily loads or weekly concentrations from the CD site, the independent variable X is daily drain flow or daily loads or weekly concentrations from the FD site, Z is a binary independent variable with Z_1 and Z_2 equal to 1 during HL and LL treatment periods, respectively. β_{0-5} are regression coefficients provided by the model and e indicates the error term.

The standard ANCOVA model assumes that the regression residuals are independent and normally distributed. Due to the high frequency sampling needed to determine drain flow and load, residuals were not independent. The error term in equation 1 was modeled with an autoregressive moving average model (ARMA) to model the autocorrelation in the data. The ARMA error term for the linear regression model can be written as:

$$e_t = \sum_{i=1}^p \phi_i (e_{t-i}) + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

where e_t is the residual (error) from the model at time t , ϕ is the autoregressive parameter, θ is the moving average parameter, p is the order of the autoregressive part, q is the order of the moving average part and ε_t is a normally distributed random error term.

A similar method has been used in other water quality studies, for example to address the correlation in nitrate and TP concentrations data by fitting a linear regression model with an autoregressive (AR) term to the data (Fields et al. 2005; Gassman et al. 2010). However, this is the first study to use the ANCOVA model with ARMA error term to quantify the water quality impacts of CD. Statistical tests were accomplished using R and the maximum likelihood estimator was used to estimate the regression models with ARMA error term. The significance of the slope and intercept for the free draining and controlled period regression

lines was tested at the $\alpha = 0.05$ and $\alpha = 0.1$ level to determine the impacts of CD on drain flow, nutrient concentrations and loads in different treatment periods.

3. Results and discussion

3.1. Drain flow

3.1.1 Annual

Drainage volume during free-draining periods was similar in FD (NE and SW) and CD (SE and NW) plots, whereas it was lower in CD plots when drainage was controlled (Figure 4). In all years, total annual drainage volume was lower in the two CD plots compared to the FD plots, including the dry years (2009, 2012, and 2016) when drainage volumes were less than 300 mm y^{-1} , and wet years (2008 and 2011) when total drained water was above 450 mm y^{-1} in the FD plots. The number of days of control varied each year depending on precipitation and field conditions, water table level, planting and harvesting dates, and crop growth stage.

The Rank Sum test results for the annual drain flow (Table 2) indicated that the difference in drainage volume between the FD and CD sites was statistically significant in both pairs. The median drainage volume was lower in CD sites by 150 mm y^{-1} and 82 mm y^{-1} in the eastern and western pairs, respectively. The range of individual annual differences was between $88\text{-}251 \text{ mm y}^{-1}$ in the eastern pair and $25\text{-}149 \text{ mm y}^{-1}$ in the western pair. Also given in Table 2 is the range of drainage volume for all plots over 10 years

317 of study period (2007 to 2016).

318 **3.1.2. Daily**

319 The ANCOVA analysis showed that the relationship between
 320 drain flow in the FD and CD plots for the free-draining period was
 321 significant (shown in Figure 5a for the eastern pair). The
 322 relationships in treatment periods (LL: Figure 5b; and HL: Figure
 323 5c) were then compared to the free draining period. The modeled
 324 relationships for eastern and western pairs (Figure 6) indicate
 325 clearly that CD decreased daily flow under LL (summer)
 326 treatment, and even more under HL (winter). This figure also
 327 indicates that the mass difference between free-draining period and
 328 treatment periods was greater at higher drain flow indicating the
 329 greater effectiveness of CD in wet conditions. The statistical
 330 comparison of these linear regression models with the ARMA
 331 residual term (Table 3) indicated that both the intercept and slope
 332 were significantly different between the free-draining period and
 333 the two treatment periods, meaning that drain flow was
 334 significantly affected by CD at both levels (summer and winter).

335 The effect of CD on daily drain flow during each treatment
 336 period was quantified by comparing cumulative observed flow in
 337 the CD sites with cumulative flow predicted using the regression
 338 equations for each period, (Table 4) to take into account the pre-
 339 treatment differences in flow between the two FD and CD plots.
 340 CD reduced drain flow during HL control (winter) between 58-

341 79% in the eastern and 43-73% in the western pair, with the
 342 average reduction of 138 mm and 111 mm per period in the eastern
 343 and western pair, respectively. The LL control period (summer)
 344 had a similar average reduction compared to HL, with the average
 345 reduction of 63 mm in the eastern and 59 mm in the western pair.
 346 The reduction was greater during the HL control period (around
 347 2/3rd of the annual reduction) in part because it occurs during the
 348 time of the year that drain flow is higher.

349 **3.2.Nitrate and phosphorus concentrations**

350 Measured nitrate-N concentration ranged from 0.3 mg L⁻¹ to
 351 28.3 mg L⁻¹ in all plots over 11 years (shown for the eastern pair in
 352 Figure 7). Also shown is the daily drain flow for this pair
 353 indicating the effect of CD on reducing drain flow.

354 Measured phosphorus concentrations mostly ranged from 0.002
 355 mg L⁻¹ to 0.5 mg L⁻¹ for SRP and from 0.004 mg L⁻¹ to 1 mg L⁻¹
 356 for TP among all sites, shown in Figure 8 for the eastern pair. Two
 357 high values in both SRP and TP concentrations may have been due
 358 to measurement errors or fertilizer application that reached the
 359 sampling point. These high values only occurred in the CD fields
 360 during the free draining or LL control periods, and for the purpose
 361 of interpolation were removed from the dataset.

362 Yearly averages of nitrate-N concentrations over the study
 363 period (Figure 9) showed that all four plots had a similar range in

the mean yearly nitrate concentrations and there were not considerable differences between the FD and CD sites. The mean concentration was 8.4 mg L^{-1} in FD and 8.5 mg L^{-1} in CD plots. The yearly mean concentrations of SRP and TP in CD plots tends to be higher than in the FD plots as shown in Figure 8. SRP had a mean concentration of 0.04 mg L^{-1} in FD plots and 0.06 mg L^{-1} in CD plots and the mean concentration of TP was 0.15 mg L^{-1} and 0.22 mg L^{-1} in FD and CD plots, respectively.

The ANCOVA analysis using linear models with the ARMA residual term was conducted only on each pair in which the relationship between sites was significant in the calibration period (Table 5). The calibration period models were statistically significant for nitrate concentration in both pairs, for SRP in the eastern pair, and for TP in the western pair. The linear models for concentrations indicated that there were no significant differences between the slope or the intercept of concentration regressions in any of the treatment levels for nitrate or TP, but the intercepts were significantly different in the SRP concentration regressions for both HL and LL control periods (Table 5, Figure 10).

The effect of CD on nutrient concentrations during each period was determined by comparing the average observed concentration from treatment periods in CD sites with the average predicted concentration using the regression equations (Table 6). Nutrient

concentrations increased in most years with CD at HL and LL in both pairs, however, as stated above (Table 5), only the increase in SRP concentrations were statistically significant.

3.3. Nitrate and phosphorus loads

3.3.1. Annual loads

The 10 years of annual nitrate-N loads from this site are among the longer datasets quantifying losses from subsurface-drained fields. The mean annual nitrate-N load in the free draining (FD) fields at this site was $30 \text{ kg ha}^{-1} \text{ y}^{-1}$. Nitrate-N median loads of $37 \text{ kg ha}^{-1} \text{ y}^{-1}$ for wet years and $14 \text{ kg ha}^{-1} \text{ y}^{-1}$ for dry years were reported by Christianson and Harmel (2015) for sites with conservation tillage in a review of around 1300 subsurface drainage nutrient load site-years of data. The mean TP load measured from FD plots was $0.54 \text{ kg ha}^{-1} \text{ y}^{-1}$, which is in the range of $0.4 - 1.6 \text{ kg ha}^{-1} \text{ y}^{-1}$ reported by King et al. (2015). This phosphorus load was mainly in particulate form, with only 28% ($0.15 \text{ kg ha}^{-1} \text{ y}^{-1}$) as SRP. These results were consistent with Bottcher et al. (1981) findings and indicated the significance of preferential flow in P transport through subsurface drains.

Time series of the annual nitrate-N, SRP and TP loads (Figure 11) indicate that throughout the study period, nitrate load was lower in CD plots, while the pattern was not constant for the SRP and TP. The mean annual nitrate-N load was $30 \text{ kg ha}^{-1} \text{ y}^{-1}$ in FD plots and $19 \text{ kg ha}^{-1} \text{ y}^{-1}$ in CD plots. The Rank Sum test results on

annual loads (Table 7) also indicated that the differences in nitrate-N load between FD and CD sites were statistically significant in both pairs. The median nitrate load was lower in CD sites by 12.8 kg ha⁻¹ y⁻¹ and 7.1 kg ha⁻¹ y⁻¹ in the eastern and western pairs, respectively. The differences in SRP and TP loads between FD and CD plots were not statistically significant. The smaller sample size (5 years) for SRP and TP could also weaken the power of the Rank Sum test. The sample size was larger for nitrate (10 years).

3.3.2. Daily loads

The linear regression models of nutrient loads in calibration period between the FD and CD plots were significant for both pairs meaning that the relationships between FD and CD sites can be statistically tested during the treatment periods. Results indicated that for nitrate load, both the intercept and slope were significantly different between the free draining period and the two treatment periods (Table 8). Visual comparison of these linear models (Figure 11) indicated a reduction in nitrate load with HL-CD (winter), in both pairs, and with LL-CD (summer), in the western pair. The relationships were more complex and not consistent for P loads in both pairs. The linear models on SRP and TP loads also showed a reduction in the slope in the eastern pair but an increase in the western pair, especially at the LL-CD, even though some of these differences were not statistically significant (Table 8). Figure 11 also indicated that the mass difference between free-draining

period and treatment periods was greater at higher loads, which coincide with periods of greater drain flow (Figure 5).

Comparing cumulative observed values from treatment periods in CD sites with cumulative predicted values, obtained from the regression equations, indicated that HL-CD reduced nitrate load between 33% to 74%, during this period, in the eastern pair and between 33% to 60% in the western pair with the average reduction per period of 7.8 kg ha^{-1} and 9.3 kg ha^{-1} in the eastern and western pairs, respectively (Table 9). The amount of reduction was lower with LL-CD compared to HL-CD, with the average reduction of 3.5 kg ha^{-1} and 4.3 kg ha^{-1} found in the eastern and western pairs, respectively. The effect of CD on P loads varied more over years compared to nitrate, and the impact of CD during HL vs. LL was not similar between the two pairs (Table 9).

4. Discussion

Comparison of cumulative annual subsurface drainage over ten years of study indicated that CD plots resulted in a statistically significant lower drainage volume than FD plots, with the median difference of 150 mm y^{-1} (39%) and 82 mm y^{-1} (25%) in the eastern and western pairs, respectively. During this decade, precipitation ranged from 800 mm y^{-1} to 1213 mm y^{-1} . The cumulative annual analysis method avoids the difficulty of accounting for the transition times immediately after changes in

458 outlet level as well as the potential lateral seepage from CD to
459 neighboring FD fields, but does not account for the pre-treatment
460 differences explicitly. However, cumulative drain flow was 7%
461 and 13% higher in CD plots during free draining periods over the
462 study period in the eastern and western pairs, respectively,
463 confirming that the FD plots were not yielding more drainage than
464 CD in general.

465 The ANCOVA model results, which take into account the pre-
466 treatment differences between FD and CD fields, indicated an
467 average reduction of 138 mm per period (68%) and 111 mm per
468 period (58%) in the eastern and western pair, respectively, when
469 the outlet was at the higher level (HL-winter) and 63 mm per
470 period (64%) and 59 mm per period (58%) average reduction when
471 the outlet was at the lower level (LL-summer). These results
472 quantify for the first time the greater reduction in drain flow at
473 higher control levels (winter), where there is sufficient drain flow
474 to control. The ANCOVA model indicated an average reduction in
475 annual drain flow of 48% in the eastern and 42% in the western
476 pair when both HL and LL treatment periods, as well as free
477 draining periods were included in the annual reduction calculation.

478 The higher reductions (48% and 42%) from the ANCOVA
479 statistical method compared to the cumulative annual method (39%
480 and 25%) are likely due to the pre-treatment differences in plot

hydrology, which are not taken into account in the cumulative method. Drain flow reductions found through both statistical methods, were higher than the 15-24% reduction found by Adeuya et al. (2012) from two fields in in northwestern Indiana. Differences in control levels, soil characteristics, weather conditions and whether drainage was controlled in the growing seasons or only non-growing seasons can lead to variability in the results from different site studies. In addition to variability among sites, the design and statistical analysis used to assess the CD impacts have also varied among previous studies, which may add to the apparent variability in results. Variations in drain flow reduction with CD obtained from the DPAC site using different statistical methods suggest the need for a method which is applicable to most sites and is reliable for comparing water quality impacts of CD from different site studies.

The impacts of CD on nitrate-N, SRP and TP concentrations were more complex and not consistent across pairs. The averages of nitrate-N, SRP and TP concentrations were slightly higher in controlled periods, however, they were not significantly different from the free-draining periods except for the SRP in the eastern pair. The non-significant difference in nitrate concentrations was similar to what the majority of other studies have reported (Fausey, 2005; Adeuya et al., 2012 and Williams et al., 2015a), although

504 some have observed lower nitrate concentration in CD fields. The
505 increase in SRP was comparable to observations from Valero et al.
506 (2007), Feser et al. (2010), and Tan and Zhang (2011).

507 Nutrient concentrations in the soil are affected by different
508 factors such as water table level, soil organic matter, and
509 temperature. CD raises the water table levels leading to anaerobic
510 soil conditions, which could be expected to increase denitrification
511 and therefore, lower nitrate concentration in drain flow. Yet, other
512 factors such as cold temperature can reduce the amount of
513 denitrification, especially when high-level control mostly occurs
514 during the wintertime. Stanford et al. (1975) found that
515 denitrification rate decreases almost ten times as the temperature
516 drops from 10 °C to 5°C. During the five years for which soil
517 temperature data were available (2011-2016) 88% of the drain
518 flow during HL controlled periods occurred when the average soil
519 profile temperature was below 10 °C. Therefore, denitrification
520 was unlikely to have significantly reduced the nitrate
521 concentration, and this is reflected in the similarity of
522 concentrations in FD and CD. P concentration in drainage may
523 also increase under CD due to anaerobic soil conditions which
524 facilitate the movement of P in the soil (McDowell et al., 2012).
525 This may explain the higher SRP concentrations during controlled
526 periods in the eastern pair.

527 Comparing actual annual values of nitrate-N load from FD and
 528 CD plots over 10 years showed a median reduction of 12.8 kg ha^{-1}
 529 y^{-1} (43%) and $7.1 \text{ kg ha}^{-1} \text{ y}^{-1}$ (26%) in CD plots in the eastern and
 530 western pairs, respectively. The ANCOVA results also indicated
 531 that CD at HL decreased nitrate-N load by 7.8 kg ha^{-1} (59%) in the
 532 eastern and by 9.3 kg ha^{-1} (57%) in the western pair. The average
 533 reduction with CD at LL was 3.5 kg ha^{-1} (54%) in the eastern and
 534 4.3 kg ha^{-1} (48%) in the western pairs. The average reductions in
 535 nitrate load were comparable to the flow reductions found in this
 536 study (HL control: 68% in the eastern pair and 58% in the western
 537 pair; LL control: 64% in the eastern pair and 58% in the western
 538 pair) indicating that the main factor contributing to nutrient load
 539 reductions in CD sites was still the reduction in drain flow, as
 540 concentrations were slightly higher (not significant) in CD fields.

541 The effects of CD on phosphorus (P) load varied more over
 542 years compared to nitrate, because there were more variations in
 543 the P concentrations than nitrate. The annual SRP and TP loads
 544 were greater in CD plots than FD plots in some years and were
 545 lower in other years, but based on the Rank Sum test results, the
 546 differences were not statistically significant. Similar to the Rank
 547 Sum test results, the ANCOVA model also indicated inconsistent
 548 results over years and across plots. Changes in SRP and TP loads
 549 were not proportional to the flow reduction, implying the

550 importance of P concentration that is affected by many factors
551 other than the water table level set by CD. CD impact on SRP and
552 TP loads quantified in the current study were not similar to the
553 values reported in the literature, such as the 80% reduction in
554 soluble P loads observed by Nash et al. (2015), and the 40% to
555 68% reduction in soluble P found by Williams et al. (2015a). P
556 concentration and load are spatially and temporally variable and
557 dependent on a combination of factors, including soil
558 characteristics, drainage design, management practices, and
559 climate variables (King et al., 2015). Additionally, in the studies
560 conducted by Nash et al. (2015) and Williams et al. (2015a), the
561 statistical approach was different than the current study and may
562 contribute to the variability in the results.

563 An uncertainty analysis on annual nitrate-N and SRP load
564 estimates at field scale indicated that estimated annual SRP loads
565 tended to be less precise and more biased than nitrate-N loads
566 estimates (Williams et al., 2015b). In order to be able to make any
567 conclusion about the effects of CD on P load, more frequent
568 concentration measurements are required, especially during storm
569 events, since storm discharge can significantly affect the P
570 transport (McDowell et al., 2001; Schelde et al., 2006; Zimmer et
571 al., 2016). Williams et al. (2015b) recommended a higher sampling
572 frequency for SRP compared to nitrate-N to yield the same

accuracy in annual SRP and nitrate-N loads estimates. In addition to the uncertainties acknowledged in the literature related to the sampling frequency and type (e.g., Birgand et al., 2010; Jiang et al., 2014; Williams et al., 2015b), there are some uncertainties related to drain flow dataset for the DPAC site due to combining measured drain flow with estimated values. Detailed explanation of uncertainties associated with measured and estimated drain flow for this site is given in Saadat et al. (2018). Beside the measurement methods, load estimation using interpolation can introduce uncertainty into the annual load estimates. However, Williams et al. (2015b) found that linearly interpolating the concentration combined with continuous flow (used in the current study) resulted in the best balance between accuracy and precision for annual nutrient load estimates.

In general, the difference between HL-winter and LL-summer control emphasizes the impacts of control level and season on drain flow and therefore, water quality benefits of CD systems. The HL-winter control during the non-growing season provided about 70% of annual water quality benefits and the other 30% was obtained by LL-summer control during the growing season. Furthermore, variation over years at one control level can be due to the different duration that drainage was controlled in each year, and whether it was a wet or dry year.

596 Despite the reduction found in drain flow with CD in this and
597 other studies, the question of the fate of the retained water, and
598 whether the nitrate reduction at the outlet of the subsurface
599 drainage system extends to the watershed scale, remains
600 unresolved. For example in Illinois, Lavaire et al. (2017) found
601 only a 10% reduction in drain flow and nitrate loads with CD when
602 two neighboring fields were both controlled, to avoid lateral
603 seepage to the FD neighboring field. Future research that quantifies
604 the effect of CD on other potential flow paths such as surface
605 runoff and lateral seepage, denitrification occurring in these
606 pathways and the potential for increasing nitrous oxide emissions,
607 would enable a more complete characterization of the impact of
608 CD.

609 **5. Conclusions**

610
611 This study evaluated the potential of controlled drainage (CD) to
612 improve water quality using ten years of field measurements with
613 two different statistical methods. The first method was a
614 cumulative annual analysis that avoids the difficulty of accounting
615 for the transition times as well as the potential lateral seepage
616 between the neighboring fields, and the second was a rigorous
617 statistical method that accounts for the pre-treatment relationship
618 between the CD and FD fields, and explicitly models dependence
619 in the data, allowing daily data to be used in the analysis.

- 620 • Results using two separate statistical methods indicate
621 that CD significantly decreased drain flow and nitrate
622 load through subsurface drainage in both eastern and
623 western pairs. Nitrate concentrations were not
624 significantly affected by CD, indicating that load
625 reduction was mainly due to drain flow reduction.
- 626 • The CD impacts on phosphorus (P) loads were more
627 complex and inconsistent over years and across plots but
628 overall during 5 years, CD decreased P loads. P
629 concentrations were not significantly different, except
630 for a significant increase in SRP concentration with CD
631 in the eastern pair.
- 632 • The higher level of outlet control during the non-
633 growing season (winter) provided about 70% of annual
634 water quality benefits while the lower level used during
635 the growing season (summer) provided about 30%. By
636 quantifying the magnitude of the increased impact, this
637 study clarifies the added water quality benefit of
638 controlling drainage at a higher level, especially during
639 the non-growing season.
- 640 • At both control levels, the effectiveness of CD was
641 greater when more drain flow or load was present in the
642 field. These results support the CD system as a reliable

management practice for reducing nitrate loads from
subsurface drains, mainly due to the reduction in flow.

Future research should investigate phosphorus impacts through
event-based sampling, and the effect of CD on other flow paths
such as surface runoff and lateral seepage to fully characterize the
impact on nutrient loads at the watershed scale.

649

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650

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667

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Table 1. Cropping sequence and fertilizer application dates and rates for the study period

Year	Crop	Application date (nitrogen or phosphorus rate in kg ha ⁻¹)								
		N Appl 1	N Appl 2	N Appl 3	N Appl 4	Total N	P Appl 1	P Appl 2	P Appl 3	Total P
2007	Corn	May-3 (41)	May-30 (206)	Oct-10 (26)	...	273	May-3 (16)	Oct-10 (53)	...	69
2008	Corn	Apr-28 (41)	Jun-17 (202)	...	...	243	Apr-28 (16)	...	...	16
2009	Corn	May-22 (34)	Jun-9 (200)	...	...	234	...	...	...	...
2010	Corn	Jan-5 (25)	Apr-19 (35)	Jun-5 (234)	Oct-5 (17)	311	Jan-5 (53)	Apr-19 (15)	Oct-5 (35)	103
2011	Soybean	...	...	...	...	...	...	...	...	...
2012	Corn	Feb-13 (22)	Apr-23 (36)	May-25 (201)	...	259	Feb-13 (46)	Apr-23 (14)	...	60
2013	Soybean	Mar-21 (18)	...	...	...	18	Mar-21 (38)	...	...	38
2014	Corn	Apr-24 (18)	May-8 (36)	Jun-1 (218)	...	272	Apr-24 (37)	May-8 (14)	...	51
2015	Soybean	...	...	...	...	...	...	...	...	...
2016	Corn	Apr-26 (33)	Jun-2 (210)	...	...	243	Apr-26 (13)	...	...	13

Table 2. Ranges of annual drain flow for each plot over 10 years and the rank sum test results on annual flow (difference = FD – CD).

Plot	Range of annual flow (mm y ⁻¹)	Pair	p-Value	Range of diff. (mm y ⁻¹)	Median diff. (mm y ⁻¹)
NE	240 - 462	Eastern	0.007	88 - 251	150*
SE	131 - 362				
SW	224 - 446	Western	0.049	25 - 149	82*
NW	140 - 334				

* Statistically significant difference between FD and CD sites at $\alpha=0.05$

Table 3. Linear model equations with ARMA errors for free draining and two different treatment periods.

Pair	ARMA errors	Free draining		HL-CD		LL-CD	
		Intercept, β_0	Slope, β_1	Intercept, β_2	Slope, β_4	Intercept, β_3	Slope, β_5
Eastern	(2, 2)	0.47	0.73	-0.05*	0.38*	0.03*	0.63*
Western	(2, 2)	0.52	0.72	0.07*	0.41*	0.15*	0.58*

* Statistically significant difference between FD and CD sites at $\alpha=0.05$

Table 4. CD impacts on cumulative drain flow during treatment periods

Treatment period	Pair	Avg. control days per year	Predicted ^a (mm)	Observed (mm)	Avg. diff. ^b (mm)	Avg. reduction ^b (%)	Reduction range ^c (%)
HL control	Eastern	142	200	62	138	68	58-79
	Western		190	79	111	58	43-73
LL control	Eastern	128	108	45	63	64	30-85
	Western		115	55	59	58	27-83

^a Determined from calibration period (free) regression equation by applying observed values from treatment period of control (free-draining) field.

^b Average of differences or reductions over 11 years.

^c Range of percent reduction over 11 years.

Table 5. Linear model equations with ARMA errors for free draining and two different treatment periods.

Variables	Pair	ARMA errors	Free draining		HL-CD		LL-CD	
			Intercept, β_0	Slope, β_1	Intercept, β_2	Slope, β_4	Intercept, β_3	Slope, β_5
Nitrate Conc. (mg/L)	Eastern	(1, 1)	0	0.772	1.398	0.927	0.767	0.82
	Western	(1, 2)	2.185	0.758	3.621	0.626	2.166	0.794
SRP Conc. (mg/L)	Eastern	(1, 0)	0	1.002	0.043**	1.25	0.048**	0.712
	Western	.....	.....	.....	.....	.....	.....	.....
TP Conc. (mg/L)	Eastern	.....	.....	.....	.....	.....	.....	.....
	Western	(1, 0)	0.137	0.18	0.188	0.575	0.143	0.314

** Statistically significant difference between FD and CD sites at $\alpha=0.05$

* Statistically significant difference between FD and CD sites at $\alpha=0.1$

Table 6. CD effects on average nutrient concentration.

Treatment period	Pair	Predicted ^a (mg L ⁻¹)	Observed (mg L ⁻¹)	Avg. diff. ^b (mg L ⁻¹)	Reduction range ^c (mg L ⁻¹)
Nitrate conc.					
HL control	Eastern	6.68	9.39	-2.71 ^d	-5.8 to -0.9
	Western	9.13	9.42	-0.29	-2.7 to 1.6
LL control	Eastern	8.27	8.98	-0.7	-2.9 to 1.9
	Western	9.85	10.62	-0.77	-2.9 to 1.1
SRP conc.					
HL control	Eastern	0.037	0.088	-0.05	-0.032 to -0.072
LL control	Eastern	0.042	0.096	-0.054	-0.161 to -0.004
TP conc.					
HL control	Western	0.172	0.294	-0.122	-0.250 to 0.014
LL control	Western	0.16	0.213	-0.053	-0.233 to 0.043

^a Determined from calibration period (free) regression equation by applying observed values from treatment period of control (free-draining) field.

^b Average of differences over 11 years.

^c Range of reduction over 11 years (2012-2016) for nitrate and 5 years (2012-2016) for phosphorus.

^d Negative values mean that controlled drainage had higher concentrations than free drainage

Table 7. Rank sum test results on annual loads (difference = FD – CD)

Pair	Nitrate-N load		SRP load		TP load	
	p-Value	Median diff. (kg ha ⁻¹ y ⁻¹)	p-Value	Median diff. (kg ha ⁻¹ y ⁻¹)	p-Value	Median diff. (kg ha ⁻¹ y ⁻¹)
Eastern	0.003	12.8*	0.55	-0.033	0.69	-0.11
Western	0.049	7.1*	0.55	-0.047	1	-0.05

* Statistically significant difference between FD and CD sites at $\alpha=0.05$

Table 8. Linear model equations with ARMA errors for nutrient loads for three periods: free draining, HL control and LL control periods

Variables	Pair	ARMA errors	Free draining		HL-CD		LL-CD	
			Intercept, β_0	Slope, β_1	Intercept, β_2	Slope, β_4	Intercept, β_3	Slope, β_5
Nitrate load (kg/ha)	Eastern	(3, 2)	0.029	0.602	-0.004**	0.377**	0.000**	0.652**
	Western	(1, 2)	0.036	0.789	0.006**	0.419**	0.015**	0.611**
SRP load (kg/ha)	Eastern	(2, 0)	0	0.85	0	0.749	0	0.443**
	Western	(1, 3)	0	0.381	0	0.46	0	0.560*
TP load (kg/ha)	Eastern	(2, 0)	0.002	0.474	0.001	0.334**	0.001	0.436
	Western	(1, 1)	0.001	0.402	0.001	0.425	0.001	0.613**

** Statistically significant difference between FD and CD sites at $\alpha=0.05$

* Statistically significant difference between FD and CD sites at $\alpha=0.1$

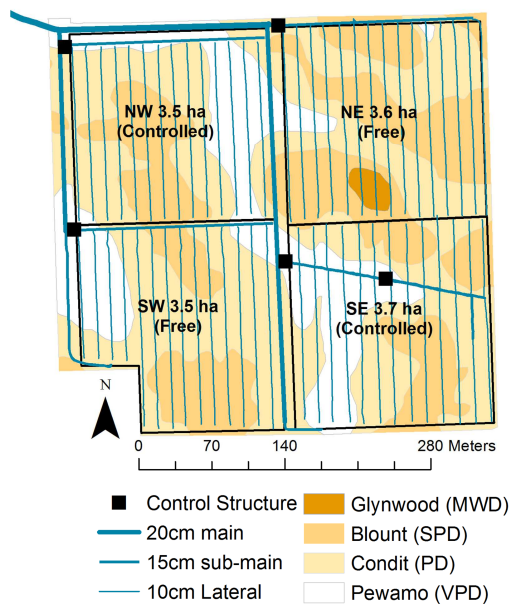
Table 9. Effects of CD on cumulative nutrient loads during treatment periods

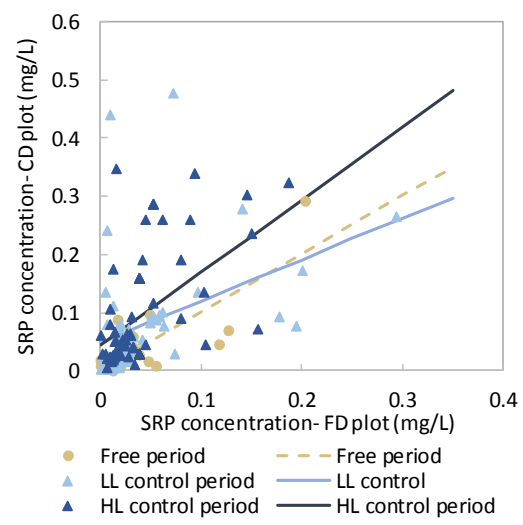
Treatment period	Pair	Predicted ^a (kg ha ⁻¹)	Observed (kg ha ⁻¹)	Avg. diff. ^b (kg ha ⁻¹)	Avg. reduction ^b (%)	Reduction range ^c (%)
Nitrate-N load						
HL control	Eastern	12.9	5.1	7.8	59	33 to 74
	Western	16.2	6.9	9.3	57	33 to 69
LL control	Eastern	7.8	4.3	3.5	54	-9 to 75
	Western	10.3	6	4.3	48	-3 to 76
SRP load						
HL control	Eastern	0.07	0.085	0.016	18	-39 to 52
	Western	0.065	0.052	0.013	10	-27 to 49
LL control	Eastern	0.092	0.057	0.035	19	-117 to 81
	Western	0.066	0.075	-0.01	0	-84 to 78
TP load						
HL control	Eastern	0.352	0.247	0.105	37	-25 to 75
	Western	0.321	0.244	0.077	27	-23 to 66
LL control	Eastern	0.3	0.149	0.151	49	17 to 87
	Western	0.259	0.204	0.055	29	-52 to 76

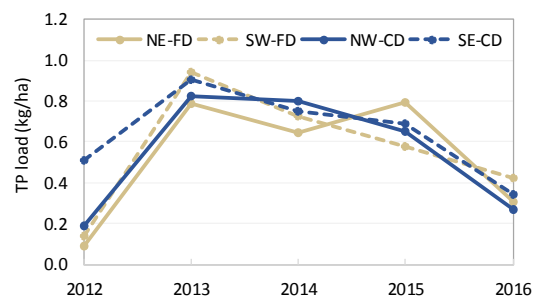
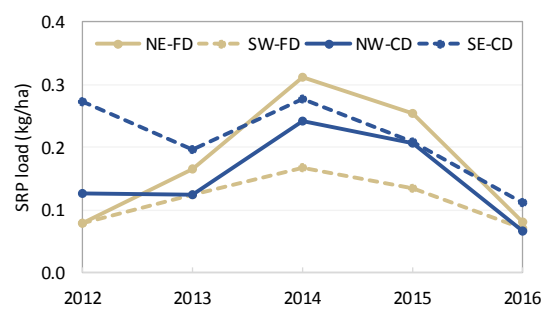
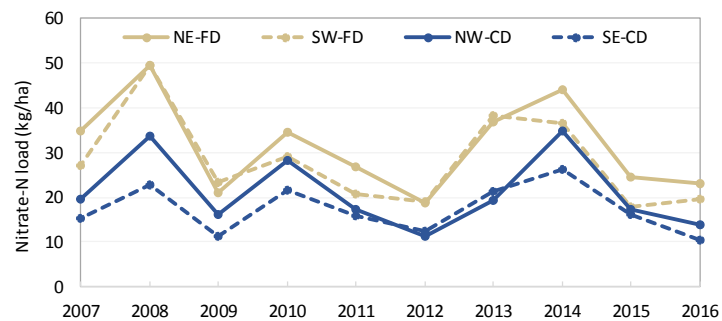
^a Determined from calibration period (free) regression equation by applying observed values from treatment period of control (free-draining) field.

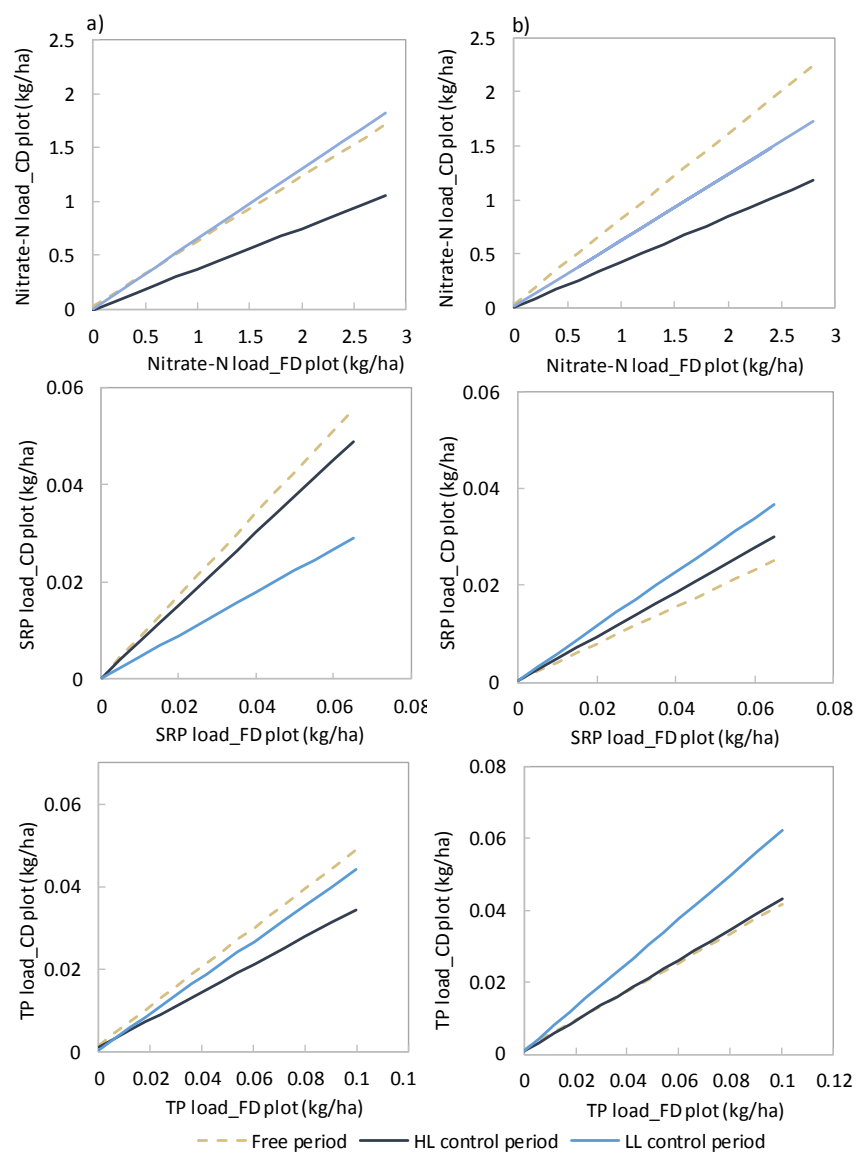
^b Average of differences or reduction over 11 years.

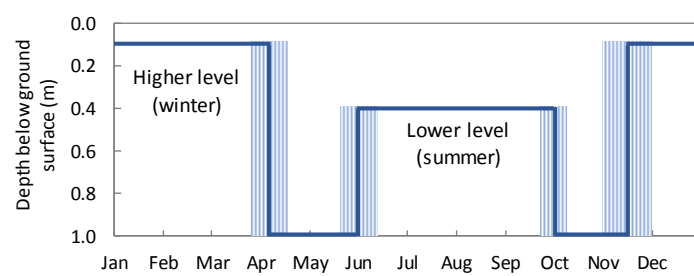
^c Range of percent reduction over 11 years (2006 to 2016) for nitrate-N and over 5 years (2012-2016) for SRP and TP loads.

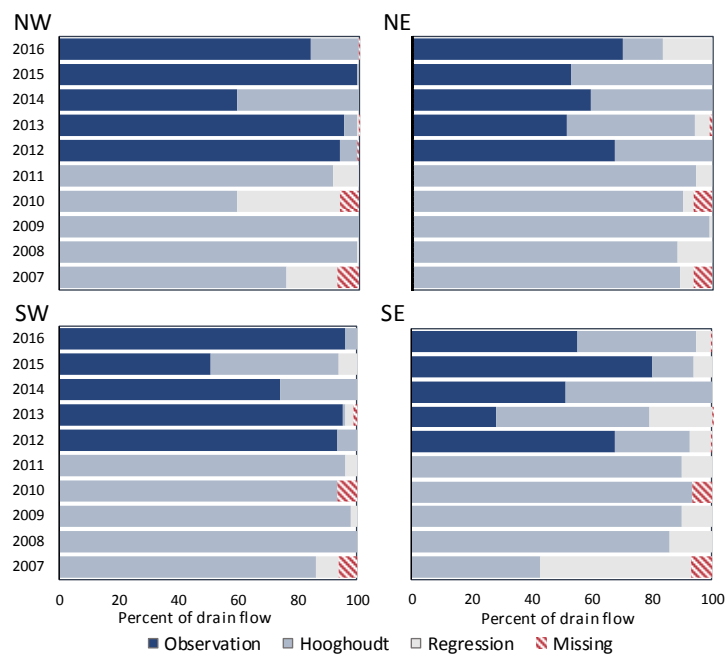


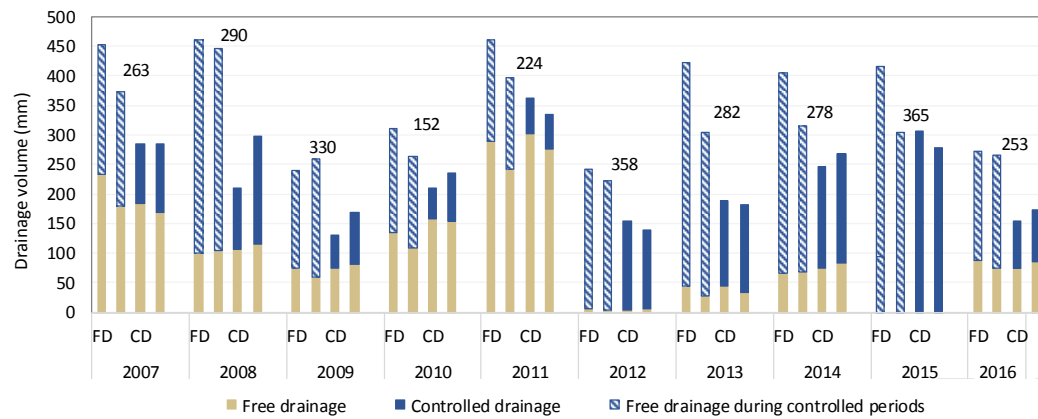


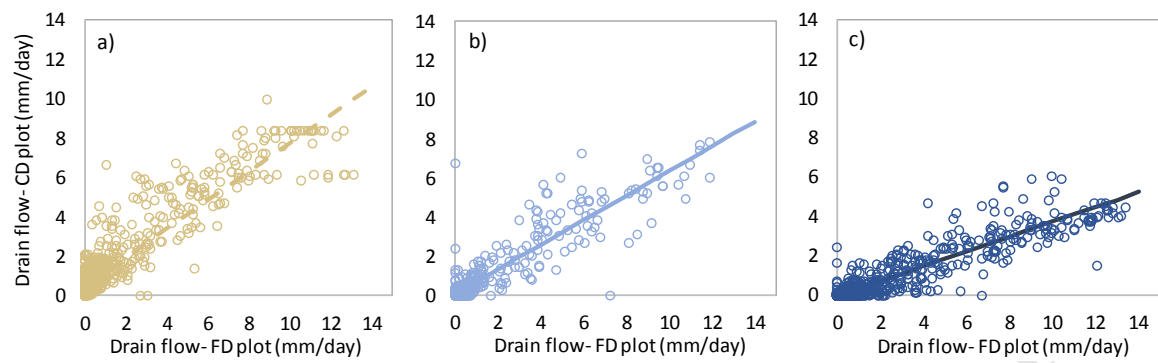


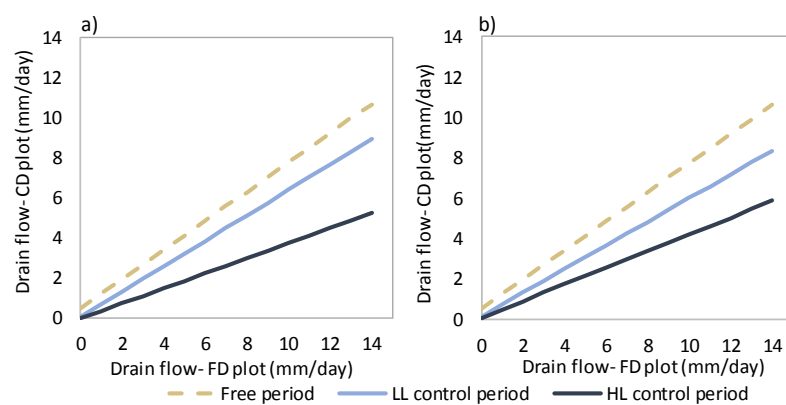


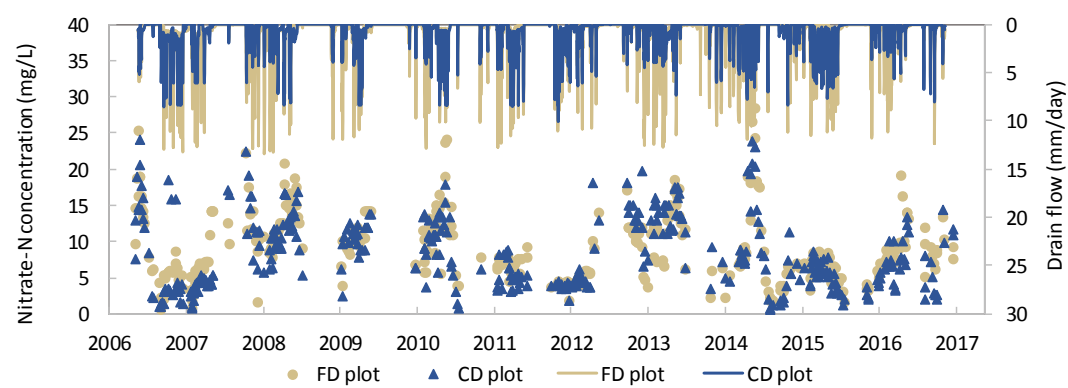


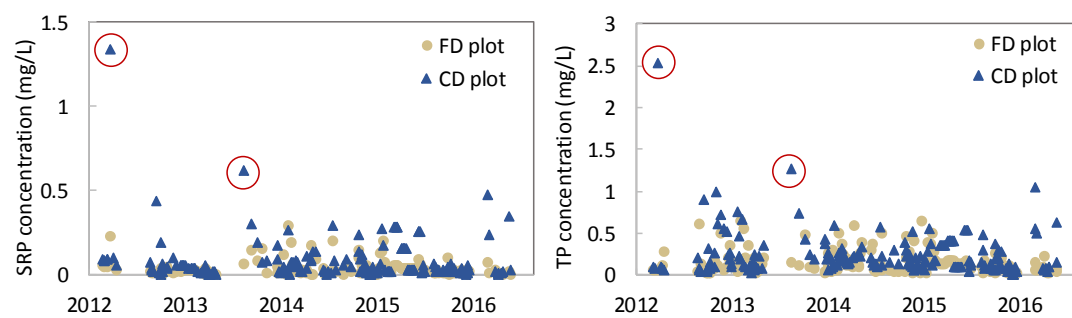


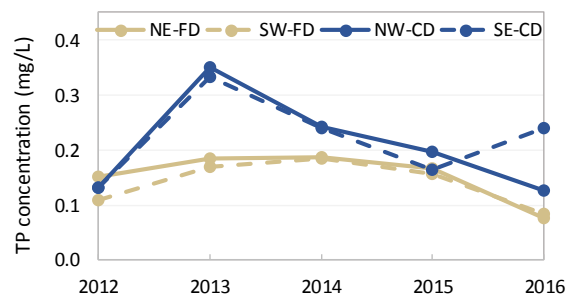
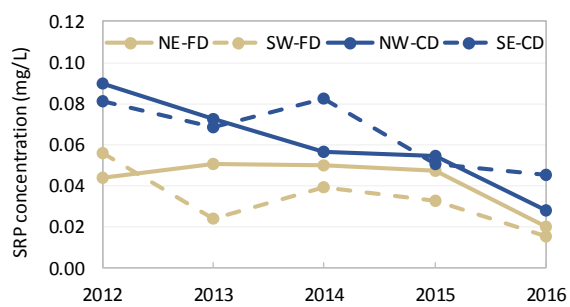
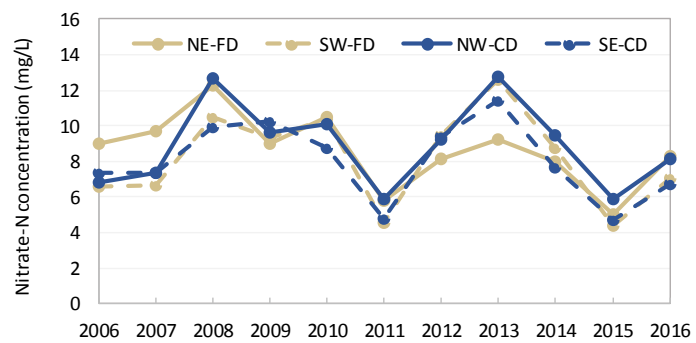












- This study quantified nutrient loads from a subsurface drainage system in Indiana, USA.
- Nitrate load was significantly lower under controlled drainage than under free drainage.
- Controlled drainage impact on phosphorus loads were both positive and negative.
- Impacts of controlled drainage were greater during high levels of outlet height control.