Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 27 January 2025
DOI 10.3389/fenvs.2024.1488925

Check for updates

OPEN ACCESS

EDITED BY
Keith Schilling,
The University of Iowa, United States

REVIEWED BY
Sergio Makrakis,
Western Parana State University, Brazil
Joseph Honings,
Iowa Geological Survey, United States

*CORRESPONDENCE
J. S. Strock,
jstrock@umn.edu

RECEIVED 30 August 2024
ACCEPTED 18 December 2024
PUBLISHED 27 January 2025

CITATION
Strock JS and Ranaivoson AZ (2025) Ditch management using low-grade weirs: an opportunity for mitigating water quality and quantity impacts.
Front. Environ. Sci. 12:1488925.
doi: 10.3389/fenvs.2024.1488925

Ditch management using low-grade weirs: an opportunity for mitigating water quality and quantity impacts

J. S. Strock* and A. Z. Ranaivoson

Department Soil, Water and Climate and Southwest Research and Outreach Center, University of Minnesota, Lamberton, MN, United States

To improve productivity, extensive agricultural areas in the Midwest United States require drainage systems consisting of subsurface drainage (tile) and open ditches. Transport of sediment, pathogens, pesticides, and nutrients from runoff and drainage from crop fields contributes to eutrophication and degradation of surface waters. Solutions are needed to improve environmental quality and reduce the negative impacts from runoff and agricultural drainage systems. This study assessed the effect of low-grade weirs on discharge and nitrate-nitrogen concentration and loss from a pair of experimental drainage ditches. One control (without weirs) and one treatment (with weirs) ditch were studied from 2017 through 2023 at the University of Minnesota, Southwest Research and Outreach Center near Lamberton, MN, United States. This study was the first evaluation of agricultural ditches, with and without low-grade weirs, and their potential to mitigate discharge and nitrogen loss in a cold climate. Stage-discharge data were collected using a data logger and bubble level sensor. Water samples were collected for water quality analysis daily using automated samplers. Analysis of the data was conducted using paired t-tests and a paired analysis approach. Analysis of covariance and linear regression of the treatment ditch against the control ditch were highly significant for nitrate-nitrogen concentration and load. The ditch with the low-grade weir was found to significantly decrease nitrate-nitrogen concentration and load. More specifically, the treatment ditch reduced discharge, nitrate-nitrogen concentration and load by 51%, 22% and 58%, respectively. The greatest discharge from the ditches occurred in March while most nitrogen losses occurred between May and June. This study provides evidence and highlights the potential of ditches equipped with low-grade weirs to reduce nitrate-nitrogen losses when compared to ditches without low-grade weirs in a cold climate. In addition, the study also emphasizes the importance of climate as a driver of nitrate-nitrogen loss from crop lands and ditches which is amplified by monthly precipitation variability.

KEYWORDS

ditch, drainage, water quantity, water quality, weir

1 Introduction

The most recently published survey of agriculture estimates 22 million ha of subsurface drained land in the United States (US) (NASS, 2017). In the Midwest US, seasonal differences in the amount and timing of precipitation and crop water demand often result in surplus water early and late in the growing season and a water deficit in summer months (Reinhart et al., 2019).

Drainage is a critical year-round water management tool for enabling productive and profitable agricultural systems. Drainage is a natural process whereby water moves across, in, through, and out of the soil. Drainage systems permit or improve crop growth and productivity by removing non-capillary water from the soil. The benefits of drainage systems include prevention of flooding through the rapid removal of surface water and non-capillary soil water, lowering shallow ground water to prevent crop stress, and creation of suitable conditions for field operations (Kaur et al., 2017). For example, although excess rainfall induced crop yield loss in tile drained landscapes, it was determined that yield losses would have been worse without artificial drainage (Li et al., 2019). While drainage has multiple benefits it also has negative impacts, it alters the quantity and quality of water drained from agricultural lands (Williams et al., 2015). Surplus inorganic nitrogen (N) and other nutrients attributed to drainage within the Mississippi River watershed stimulate algal growth and eutrophication and ultimately contribute to the hypoxic zone in the Gulf of Mexico (Fennel and Laurent, 2018; Rabalais and Turner, 2019).

Solutions are needed to temporarily detain drainage water on the landscape and reduce nutrient losses to improve environmental quality and reduce negative impacts from drainage systems. Simultaneously, mitigation strategies are needed to supplement conventional agricultural best practices, for example, the 4R's of nutrient stewardship (Right source, Right rate, Right time, and Right place), to obtain reductions in non-point source agricultural nutrient loss. Technologies are needed to achieve peak flow reduction and removal of nutrients from agricultural drainage water without taking land out of production, they need to be low maintenance, and provide multiple ecosystem services. In watersheds where artificial drainage is practiced, surface and subsurface runoff from agricultural lands is often carried by a network of drainage ditches that function as headwater streams. Managing agricultural drainage ditches has potential for improving environmental quality benefits related to water quantity, quality, habitat, and biodiversity.

Ditch systems are typically small (1–2 m wide) historically natural streams that have been artificially deepened and straightened, or new channels, constructed to serve as an outlet for field drainage systems. Agricultural ditches are generally ephemeral aquatic ecosystems used to maintain optimal soil moisture in adjacent agricultural fields. Ditches act to transport not only water, but also nutrients, sediment, pathogens, and pesticides from agricultural fields to small streams and larger rivers (Olson, et al., 2016; Faust et al., 2018). These ditches have nominal hydraulic attenuation capacity, and minimal capacity for biogeochemical processing and natural retention of dissolved or particulate materials. Under low-flow conditions, ditches exhibit similar chemical and microbiological functions as wetlands (Moore et al., 2005; Martin et al., 2021) and appropriate management practices can be used to promote ecosystem services such as nutrient removal. Previous studies reported managed agricultural drainage ditches as potentially an efficient nutrient mitigation strategy (Kröger et al., 2008; Kröger et al., 2014). The challenge with many of these studies is that they were conducted in a warm climate, Mississippi, where the average annual temperature is 18°C and the mean minimum and maximum are −9°C and 32°C, respectively. It is important to know if managed drainage ditches have the same potential in cold northern climates like Minnesota, where the average annual temperature is 7°C and the mean minimum and maximum are −20°C and 27°C, respectively.

Traditionally, drainage ditch systems have been conveyance systems to eliminate water from the landscape as quickly as possible. Modifications to ditch systems have incorporated installation of different control measures including flashboard riser systems (Evans et al., 1995) and low-grade weirs (Kröger et al., 2008) to manage water flow in drainage ditch systems. Implementation of low-grade weirs has been shown to be effective in reducing N concentration and load to receiving waterbodies (Kröger et al., 2012). The N removal efficiency of microbial denitrification and denitrification rate depends on factors including the availability of carbon and adequate ambient temperature. In previous experiments, low-grade weirs were studied primarily in the southern United States and their performance in cold climates typical of northern latitudes remains unclear. Our approach consists of the installation of a low-grade weir within a ditch system in a cold climate. The purpose of the weir is to increase hydraulic retention time (HRT), decrease flow velocities, and create zones of inundation (Kröger et al., 2008), the cumulative effect of which is expected to be the establishment of conditions suitable for N cycle processes such as denitrification and bioaccumulation (Littlejohn et al., 2014; Kröger et al., 2014). Diverse vegetation communities grow in ditches and often promote biological nutrient uptake and removal (Faust et al., 2018). In addition, vegetation increases hydraulic friction in the ditch channel thereby promoting reduced flow velocity in the water column that increases HRT which further enhances the opportunity for nutrient removal (Faust et al., 2018; Nifong et al., 2019). A recent study in the Lower Mississippi River Basin demonstrated these beneficial effects of vegetative cover and residence time in a managed ditch system (Nifong et al., 2019).

The objective of this research was to evaluate the effectiveness of an agricultural drainage ditch management strategy in a cold climate to temporarily increase water storage and reduce nitrogen loading from agricultural runoff. Specifically, this field study evaluated the effectiveness of low-grade weirs on drainage discharge and nitrate-nitrogen concentration and loss from a pair of experimental drainage ditches in the upper Midwest, United States.

2 Materials and methods

2.1 Description of research site

A field experiment was conducted at the University of Minnesota, Southwest Research and Outreach Center (SWROC), near Lamberton, Minnesota (lat. N: 44°14′36″, lon. W: 95°18′20″) to study the potential of ditches equipped with low-grade weirs to

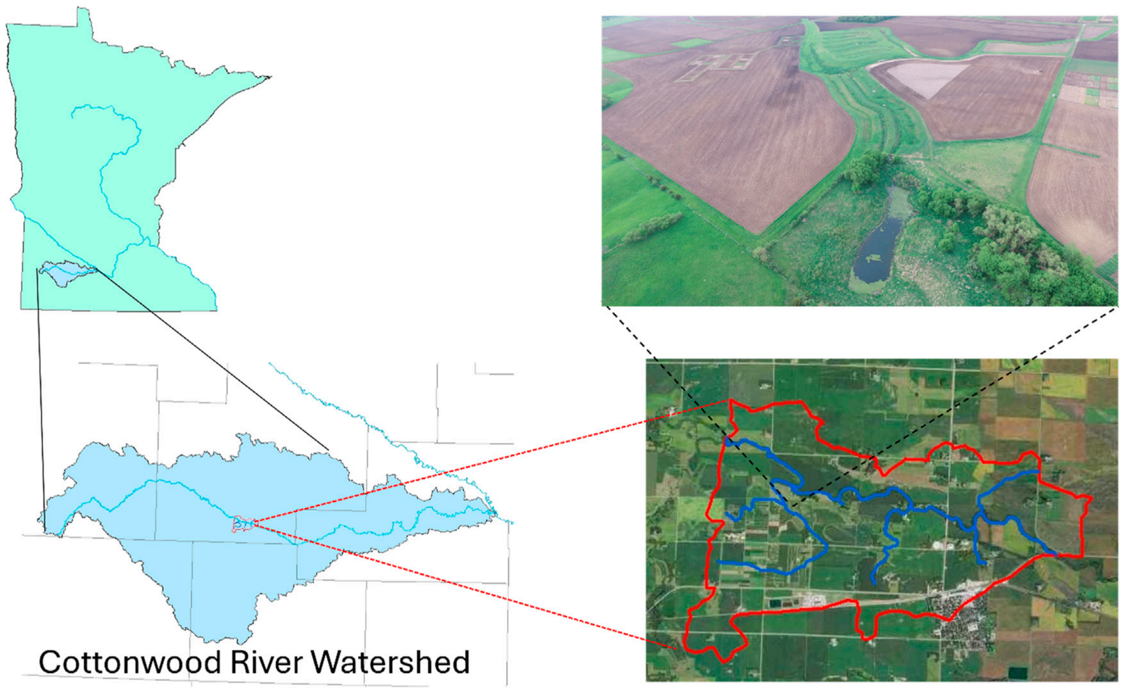

FIGURE 1
Location of ditch research facility in southwest Minnesota.

reduce nitrate-nitrogen (NO_3-N) losses when compared to ditches without low-grade weirs in a cold climate. The climate of the region is characterized as interior continental with cold winters and moderately hot summers with occasional cool periods. Average annual temperature is 7°C, with monthly extremes ranging from 32°C in July to −13°C in January. The long-term total annual precipitation at SWROC is 710 mm, considered adequate to grow crops without irrigation because most of it (69%) falls during the growing season from April to September.

The field research site was located in the Cottonwood River Major Watershed of southwest Minnesota. Farming is the principal segment of the economy in this watershed consisting primarily of row crop production of corn and soybeans. Land cover in the watershed consists of approximately 85% cultivated cropland, 8% grassland (including CRP land), 1% woodland, and 6% other land. The watershed landscape is characterized as having a complex mixture of gently sloping (2%–6% slope) well drained loamy soils and nearly level (0%–2% slope) poorly drained loamy soils formed in glacial till. Poorly drained soils are highly productive due to an extensive network of subsurface tile drainage and open-ditches.

2.2 Ditch features, design criteria, and management

This experimental site was established to identify the effectiveness of ditch management strategies to increase water storage and decrease nutrient discharge from an agricultural landscape. Strock et al. (2005) described the development of a vegetated ditch research facility in the glacial till plain within the Northern Corn Belt Plain region of southern Minnesota. Construction of the experimental channels was completed in late summer 2002. Briefly, two side-by-side, 200 m long, experimental vegetated ditch channels receive surface runoff and subsurface drain flow from the surrounding farmland (Figure 1). The drainage area consists of 132-ha section of the watershed. The area contributing water from surface runoff to the ditch facility is 73 ha, and the area contributing water from subsurface tile drainage is 59 ha. Of the total area contributing water from subsurface drainage, 21 ha lies outside the boundary of the total area contributing surface runoff.

The geometry of the experimental channels was typical of drainage channels in the region with bottom width of 1.5 m, height of 1.2 m, 2:1 side slopes (H:V), and bed slope of 0.1%. The peak discharge capacity of each experimental channel was 1.4 m^3s^{-1}. Water flows through 0.76 m (2.5 foot) H-flumes at the outlets of the experimental channels. A 1.5 m wide by 3.0 m long by 0.76 m deep polyvinylchloride (PVC) approach sections come before the H-flume in each channel. Water level in the treatment ditch is regulated using PVC weirs. Each weir was manufactured with a rubber seal to assure a tight fit to prevent leakage. Weirs measure a minimum of 0.15 m in height. Two weirs were stacked to achieve the desired water level control height, 0.3 m in this experiment. Once installed, the weirs were left in place continuously. The ditches consisted of mainly perennial vegetation, typical of the Midwest. Dominant species included *Poa palustris, Sagittaria latifolia, Phalaris arundinacea, and Bromus inermis.* Vegetation density was not quantified to determine if there were differences between the control and treatment channels.

The design for this project consisted of a control and treatment ditch and two time periods, a calibration and a treatment period (Figure 2). The calibration period was 2 years in length, 2004–2005.

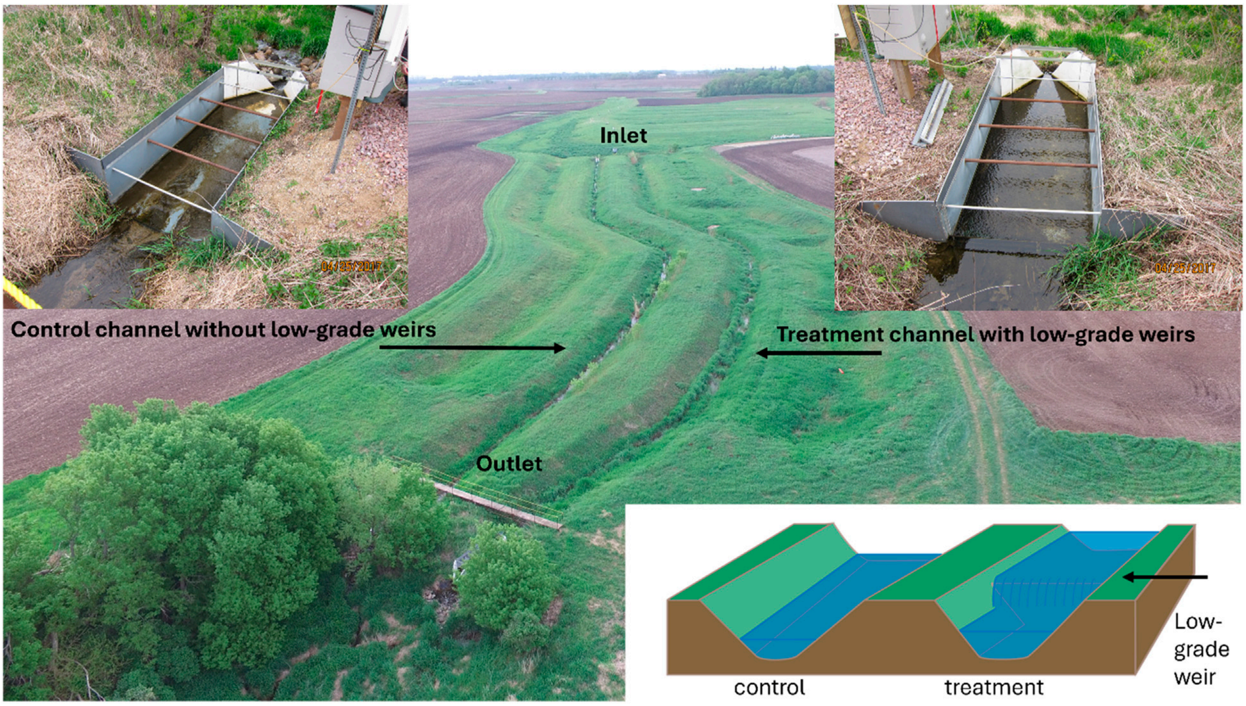

FIGURE 2
Experimental ditch facility showing inlet, outlet, treatment and control channels including a picture and drawing of the influence of the low-grade weir on water elevation in the treatment ditch.

In 2006, the treatment ditch received the prescribed experimental treatment, installation of a 0.3 m low-grade weir, while the control ditch remained unchanged. The control ditch served as a check for climatic and other variations during the year. The treatment period for this study ranged between 2017 and 2023. The treatment period was partitioned into three groups based on annual rainfall amounts: wet years: 2018–19, dry years 2021–2022, and normal/average years: 2017–2020–2023. In this project, the variables of interest were ditch discharge rate, m^3 d^{-1}, flow-weighted nitrate concentration (FWMNC), mg L^{-1}, and NO_3^--N load, kg.

2.3 Monitoring, water sampling and analysis

To study the effects of ditch management on surface and subsurface drainage discharge and water quality from the surrounding agricultural landscape, source water and ditch outflows were measured the watershed converges to a common equalization basin prior to being discharged to the two experimental ditch channels. This configuration helped minimize variability from surface runoff and subsurface drainage source water and was important to reduce high frequency fluctuations of water and nutrient inputs to the ditch channels and to promote complete mixing of source waters. After mixing water was equally distributed to each experimental channel. Source water flows and ditch outflows were measured from 2003 to 2009 and then again from 2017 to the present. The time gap between 2009 and 2017 was due to budget limitations. Inflow data was not collected between 2017 and 2020, due to equipment availability and budget limitations.

Daily mean values of drainage volume were calculated from continuously recorded stage data using stage-discharge relationships for the H-flumes. Each H-flume was instrumented with an OTT bubble level sensor (OTT Hydromet, Germany). An ISCO 3700C compact portable sampler (Teledyne ISCO, Inc., Lincoln, NE) was installed after each water metering H-flume. The ISCO 3700 samplers were used collect composite and discrete water samples from each experimental ditch based on base flow or storm flow hydrograph conditions. A Campbell Scientific CR1000 data logger (Campbell Scientific, Logan UT) was used to control the portable sampler and to collect the water level data.

A data logging program, using CRBasic programming language, was created to automatically record, store, and organize data from the bubble level sensor to the data logger for monitoring ditch hydrograph response to storm flow. The data logger program was also designed to collect a composite daily sample during base flow conditions and discrete samples during the rising, peak and recessional components of the hydrograph. Between 2017 and 2023 a total of 2,326 water samples were collected and analyzed. The distribution of samples by year was as follows, 290 in 2017, 449 in 2018, 781 in 2019, 283 in 2020, 190 in 2021, 178 in 2022, and 86 in 2023. The combination of water flow measurement and nutrient concentration allows for estimation of contaminant loading to surface water. Discharge was continuously measured, and water samples collected between ice-free periods in order to minimize potential damage to instrumentation.

Water samples were analyzed for NO_3^--N and dissolved reactive phosphorus (DRP) concentration. All chemical analyses were completed using Lachat 8500 Flow Injection Analyzer (Hach, Loveland, CO). Samples were typically collected within 24 h of a storm event and either frozen or stored at 4° C for analysis within 24 h. Samples were filtered through a 0.45 μm nitrate-cellulose membrane before analysis of NO_3^--N and DRP. Dissolved reactive P was analyzed using colorimetric analysis by the molybdate-blue/ascorbic acid method (10-115-01-1-Q) at 880 nm. Nitrate-nitrogen was analyzed using colorimetric analysis by the cadmium reduction method (10-107-04-1-A) at 520 nm.

Nutrient concentration and water volume provided a nutrient load for respective baseflow and storm events. Drainage area was the total area of farm contributing surface and subsurface drainage to the experimental ditches. Nitrogen and phosphorus loads (kilograms and grams, respectively) were evaluated on a per hectare basis. Loads, which represent the actual nutrient load leaving a ditch at the outflow sampling station represented the daily load attained within a ditch as a result of the combination of surface and subsurface flow processes.

2.4 Statistical analysis

A paired watershed design was used to evaluate the impact of ditch management on water quantity and quality. Statistical tests on the experimental data were run on a JMP 15.0 Pro platform (JMP, 2019). The alpha value level of confidence was set at 0.10 for field experiment. The main data treatment for this set of ditch records was based on pairing all daily records from the control and the treatment ditch for the variables of interest. This data pairing extended to both the calibration (2004–2005) and the treatment periods (2017–2023). The partitioned data were then tested using analysis of covariance (ANCOVA) to compare linear relationships (slope and intercept) between the control and the treatment ditches over the calibration and treatment periods.

In addition to the paired watershed statistical method, two other methods were applied to assess significant differences between the parameters listed above: t-test and mean comparisons with Tukey HSD. A t-test was used in comparing discharge rate, m^3 d^{-1}, FWMNC, mg L^{-1}, and NO_3-N load, kg over the entire length of the treatment period, 2017–2023, based on monthly average data. The Tukey HSD mean comparison handled relative contribution of monthly averages over the control and the treatment ditches.

3 Results

3.1 Precipitation characteristics

The study period, 2017–2023, provided an opportunity for evaluation of ditch management in a northern latitude under contrasting climatic conditions. Precipitation data was grouped in two ways. First, according to experimental interval, either the calibration or treatment period. Second, it was also organized into three bins representing dry, normal, and wet conditions. Annual precipitation averaged 838 mm over the calibration period and was 14% wetter than normal. During the treatment period, from 2017 to 2023, annual precipitation ranged from 511 mm (30% below normal) in 2022 to 1,010 mm (37% above normal) in 2019 (Table 1). Annual precipitation was highly variable during the treatment period, including two below-average years (2021 and 2022), three nearly normal/average years (2017, 2020, and 2023), and two above-average years (2018 and 2019).

3.2 Inflow and outflow

Water flow is seasonal, with higher flows normally from April through June when spring snowmelt combines with spring rainfall and seasonally high subsurface drainage flow. Based on annual observations over several decades, on average, subsurface drainage begins between the middle of March and the beginning of April, depending on air temperature, the presence or absence of snow and frost depth. During a typical year, drain flow ends in mid-to late-July. Soils in southern Minnesota are prone to snowmelt and/or rainfall runoff from early spring or early summer. Early-spring to early-summer are periods when the soil surface is relatively bare depending on the amount of residue leftover from primary and secondary tillage, if tillage is part of field management. In addition, normally annual row crops like corn and soybean are seedlings at this time with very small leaf areas leaving soil exposed to rain drop impacts.

Flow data collected during the calibration period is shown in Table 1. Annual discharge and N concentration varied between the 2 years due to differences in amount and timing of annual precipitation (Supplementary Figure S1). The discharge data represented a low flow year, 2004, and a high flow year, 2005. The mean discharge was 772 m^3.

Between 2021 and 2023 observed inflow to the ditches in the form of snowmelt runoff/surface runoff and subsurface drainage was highly variable and at times non-existent (Figure 3). Inflow was dominated by subsurface drainage which occurred in 16 months of this 3-year period. In contrast, snowmelt runoff/surface runoff occurred in 4 months over the same time span. Spring (March to May) inflow from subsurface drainage was usually the time when discharge was highest, with lower, secondary peaks of discharge occurring in summer and autumn. Continuous subsurface drainage between November 2021 and March 2022 was highly unusual. The greatest snowmelt runoff/surface runoff volume over this 3-year period, 63,736 m^3, was recorded during June 2023. As noted previously, precipitation during this year was slightly above average.

The first 6 months of 2021 were exceptionally dry, and no subsurface drainage was observed (Figure 3). Above average autumn precipitation from August through October, coupled with low evaporation and low to no transpiration, contributed to subsurface drain flow into the ditches. Frequent freeze/thaw cycles between November 2021 and March 2022 contributed to sustained subsurface drain flow into the ditches. Average to slightly above average precipitation between March and May 2022 resulted in the highest monthly subsurface drain flow recorded over this 3-year period, 99,623 m^3, in May. Subsurface drain flow in 2023 was much closer to normal with respect to timing and magnitude.

Hydraulic retention time was estimated in the spring of 2021 using a conservative bromide tracer. The HRT of the control channel was, on average, <30 min, whereas the HRT of the treatment channel was 11 h (data not shown). Between 2017 and 2023, implementation of the low-grade weir resulted in a 51% reduction in discharge from the control ditch, 1,057,530 m^3,

TABLE 1 Annual mean daily discharge rate, flow-weighted mean nitrate concentration (FWMNC), and mean nitrate loads for ditch parameters over the calibration and treatment periods.

Period	Year	Precipitation mm	Flow days	Control			Treatment		
				Discharge m^3	FWMNC mg L^{-1}	Load kg	Discharge m^3	FWMNC mg L^{-1}	Load kg
Calibration	2004	753	137	481	23.2	11.5	475	22.4	10.9
	2005	923	107	1,062	22.9	25.9	1,427	25.3	31.2
Treatment	2017	763	142	1,100	11.5	11.5	620	6.4	4.1
	2018	977	186	1,130	7.9	8.3	615	7.1	5.0
	2019	1,010	233	1,559	7.9	9.9	581	6.0	3.2
	2020	676	160	745	5.5	4.4	267	3.4	1.0
	2021	601	183	223	4.4	1.0	218	2.6	0.8
	2022	511	127	644	7.2	5.2	335	6.8	2.5
	2023	765	127	678	8.6	6.2	409	8.2	3.4

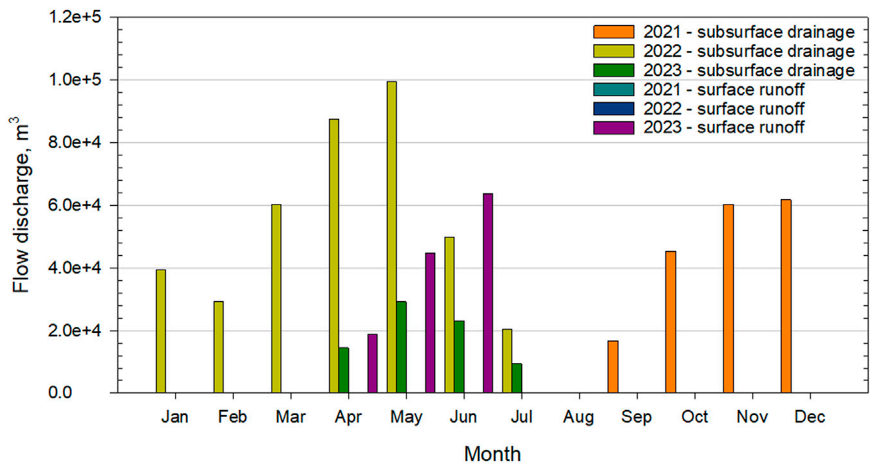

FIGURE 3
Monthly ditch inflow between 2021 and 2023.

TABLE 2 T-test for mean monthly discharge, flow-weighted mean nitrate concentration (FWMNC), and nitrate-nitrogen (NO_3^-N) load between 2017 and 2023.

Years	Station[a]	Parameter	Units	n	Mean	Std Err	Difference	DF	Prob < t
2017–23	CTL	Discharge	m^3 d^{-1}	43	976	183	−522	53	0.0049
2017–23	TRT	Discharge	m^3 d^{-1}	43	454	66			
2017–23	CTL	FWMNC	mg L^{-1}	43	6.8	0.7	−2.1	82	0.0025
2017–23	TRT	FWMNC	mg L^{-1}	43	4.7	0.5			
2017–23	CTL	$NO3^-$-N Load	kg d^{-1}	43	7.1	0.6	−3.2	72	0.0001
2017–23	TRT	$NO3^-$-N Load	kg d^{-1}	43	3.9	0.5			

[a]Control, CTL; Treatment, TRT.

TABLE 3 Mean daily discharge, flow-weighted mean nitrate concentration (FWMNC), and mean nitrate load for paired ditch comparison during the calibration and treatment periods.

Variable	Calibration		Treatment		Change, %
	Control	Treatment	Control	Treatment	
Wet years, 2018–2019					
Discharge, m^3d^{-1}	362	451	1,370	596	-32
FWMNC, mg L^{-1}	22.9	22.1	7.9	6.5	71
Nitrate load, kg	8.3	9.7	9.2	4.0	59
Dry years, 2021–2022					
Discharge, m^3d^{-1}	362	451	246	123	73
FWMNC, mg L^{-1}	22.9	22.1	5.1	3.1	86
Nitrate load, kg	8.3	9.7	1.6	0.4	96
Average years, 2017, 2020, 2023					
Discharge, m^3d^{-1}	362	451	694	199	56
FWMNC, mg L^{-1}	22.9	22.1	7.0	3.0	86
Nitrate load, kg	8.3	9.7	4.8	0.7	93

compared to 514,905 m^3 from the treatment ditch. Discharge reduction from the ditches based on climate conditions (dry, average, wet) was linear. The smallest reduction in discharge between the control and treatment ditches occurred during the dry years, followed by the average years, with the greatest discharge reduction occurring during the wet years, 33%, 49%, and 56% respectively.

There was a statistically significant difference in mean daily discharge volume between the treatment and control ditch from 2017 through 2023 with the treatment ditch discharge being 53% lower than the control ditch, on average by 522 m^3 (Table 2). During the 2 years of below average precipitation, there were 183 days of flow in 2021 and 127 days in 2022 (Table 1). During the 2 years of above average precipitation, there were 186 days of flow in 2018 and 233 days of flow in 2019, respectively (Table 1). During the 3 years of average precipitation there were 142, 183, and 127 days of flow in 2017, 2020, and 2023, respectively (Table 1). It can be seen from these data that there were nearly the same number of days of ditch outflow during 2018, 2020, and 2021 representing a wet, average, and dry year, respectively. Thus, although snowmelt runoff and precipitation affected ditch outflow, the number of days of ditch outflow were not always consistent or predictable.

Under ideal circumstances, a calibration period would comprise the full range of expected conditions, dry, normal, and wet, but capturing the normal and wet end of the range helps quantify important hydrologic behavior and concomitant nutrient transport. Analysis of covariance was used to statistically analyze post treatment results between the control and treatment ditches. The results were grouped according to precipitation regimes as either wet, average, or dry conditions compared to the 30-year normal.

Using ANCOVA, there were differences in ditch discharge between calibration and treatment period regressions under wet, dry, and average conditions. Under wet conditions, the difference represented a shift in the regression toward lower discharge from the treatment ditch following implementation of the low-grade weir in relation to the unmanaged control ditch. During the treatment period, for wet years, discharge from the treatment ditch was negative indicating that discharge increase by 32% compared to the calibration period using the calibration equation and values observed during the treatment period (Table 3). Likewise, ANCOVA indicated that there were reductions in ditch discharge during dry and average years following the implementation of the low-grade weir. Using the calibration equations, this represented a reduction of 73% under dry conditions and 56% under average conditions (Table 3).

Monthly distribution and magnitude of mean daily outflow from 2017 to 2023 for the control ditch is found in Figure 4A. Overall, this figure shows that the majority of ditch outflow occurred during the 3-month period, March to May. In general, ditch outflow gradually declined between May and August as plant growth accelerated and rates of evaporation and transpiration increased. Ditch outflow began to increase in September and October in years when fall precipitation recharged the soil water content. No ditch outflow occurred in January and February when soil was continuously frozen. Major events that resulted in significant ditch outflow occurred in the early spring, March and April, of 2019 (Figure 4A). Other periods of high input that resulted in ditch outflow were early spring to mid-summer, April to July, and autumn, September and October, of 2018. There was a total absence of ditch outflow from April to September 2021 due to prolonged drought conditions (Figure 3).

Monthly distribution and magnitude of ditch mean daily outflow from 2017 to 2023 for the treatment ditch containing the low-grade weir is found in Figure 4B. Overall, this figure shows that monthly distribution of ditch outflow from the treatment ditch was similar to that of the control ditch. In contrast, the magnitude of the treatment ditch outflows for all months were lower than those from

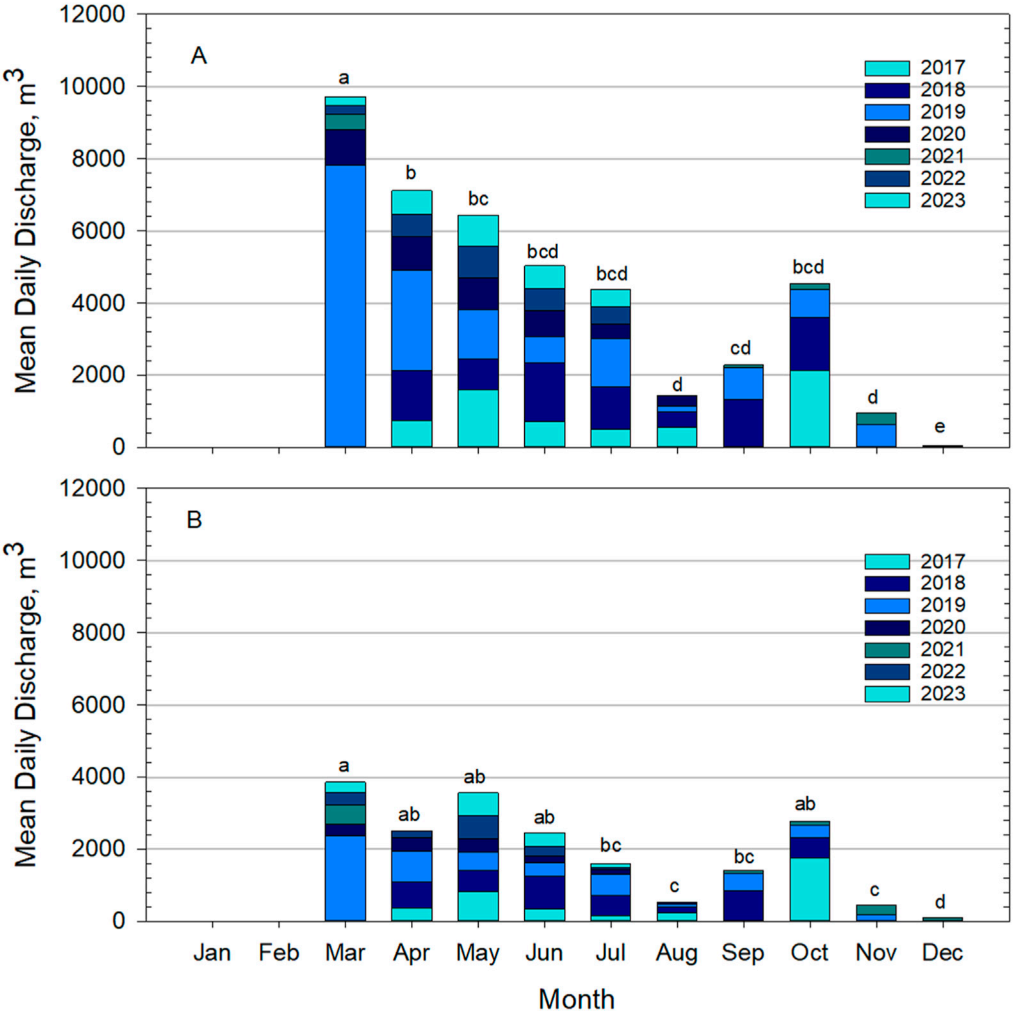

FIGURE 4
Monthly control **(A)** and treatment **(B)** ditch outflow between January and December. Means followed by the same lowercase letter are not significantly different at $P \leq 0.10$.

the control ditch. For the 3-month period between March and May, the mean monthly outflow for the treatment ditch was 56% lower than the treatment ditch. Between June and August, and September and November the outflow from the treatment ditch was reduced by 58% and 41%, respectively. This indicated that the low-grade weir was successful at increasing the water storage capacity of the control ditch.

3.3 Nitrogen concentration and loss

The processes that control nitrogen in aquatic environments include a combination of chemical and biological processes. Once in an aquatic ecosystem, such as a ditch, nitrogen is highly chemically and biologically active, undergoing numerous transformations and moving between benthic sediments and water column, and between the biotic and abiotic environment (Durand et al., 2011). In shallow flowing systems like ditches, biotic transformations of nitrogen are the dominant processes and include the autotrophic and heterotrophic uptake of nutrients from the water, assimilation into biomass, and release by excretion and microbial decomposition (Birgand et al., 2007). In addition, plants can take up nutrients from sediment pore water via roots or directly from the ditch water column. Under anaerobic conditions, denitrifying bacteria use nitrate as an electron acceptor to oxidize organic matter, thus reducing NO_3^--N to N_2O to N_2 during the process of denitrification.

3.3.1 Nitrogen concentration

Over the experimental period, from 2017 to 2023, implementation of the low-grade weir resulted in a 22% reduction in flow-weighted mean nitrate concentration (FWMNC) from the control ditch compared to the treatment ditch (Table 1). There was also a statistically significant difference in monthly FWMNC between the control and treatment ditch during the same period although the difference was small, on average 2.1 mg L^{-1} (Table 2). Between 2017 and 2023, the monthly FWMNC for the control ditch was 6.8 mg L^{-1} whereas the treatment ditch was 4.7 mg L^{-1}. This reduction in FWMNC is notable as it is somewhat uncommon to observe a significant reduction in nitrate concentration. Kröger et al. (2012), studying ditches in Arkansas, showed no significant reduction in NO_3^--N concentration from ditch systems with and without weirs. When comparing the FWMNC based on climatic conditions, during the 2 years of below average precipitation (2021 and 2022) the daily FWMNC averaged 5.8 mg L^{-1} for the control ditch and the treatment ditch averaged 4.7 mg L^{-1} (Table 1). During the 2 years of above average precipitation (2018 and 2019) daily FWMNC averaged 7.9 mg L^{-1} and 6.6 mg L^{-1} for the control and treatment, respectively (Table 1). During the 3 years of average precipitation (2017, 2020, and 2023) daily FWMNC averaged 8.5 mg L^{-1} and 6.0 mg L^{-1} for the control and treatment ditches, respectively (Table 1). It was also apparent that the daily FWMNC for both ditches from the back-to-back dry years, 2021 and 2022, to 2023, increased on average by 1.6 mg L^{-1} and 0.7 mg L^{-1}. This rise coincided with an increase in mean daily discharge from 436 m^3 during 2021 and 2022 to 678 m^3 in 2023.

Statistical analysis using ANCOVA, showed that there were differences between calibration and treatment period regressions for daily FWMNC under wet, dry, and average conditions. Under wet conditions, the difference represented a shift in the regression toward lower FWMNC from the treatment ditch following implementation of the low-grade weir in relation to the control ditch. Overall, the FWMNC of the treatment ditch was reduced by 71% using the calibration equation and values observed during the treatment period (Table 3). Likewise, ANCOVA indicated that there were reductions in daily FWMNC during dry and average years following the implementation of the low-grade weir. Using the calibration equations, this represented a reduction of 86% under dry and average conditions, respectively (Table 3).

3.3.2 Nitrate-nitrogen loss

Precipitation is the driving force for hydrologic relationships and in turn is a dominant factor in nutrient transport. Between 2017 and 2023, implementation of the low-grade weir resulted in a 58% reduction in NO_3^--N from the control ditch, 8,423 kg, compared to 3,314 kg from the treatment ditch (Table 1). Nitrate-nitrogen load reduction from the ditches based on climate conditions (wet, average, dry) was linear. In contrast to discharge, the smallest reduction in NO_3^--N load between the control and treatment ditches occurred during the wet years, followed by the average years, with the greatest load reduction occurring during the dry years, 56%, 62,% and 68% respectively.

There was a statistically significant difference in mean monthly NO_3^--N load from the control ditch compared to the treatment ditch between 2017 and 2023 (Table 2). The mean monthly NO_3^--N load from the control ditch was 7.1 kg while the treatment ditch averaged, 3.9 kg, a difference of 3.2 kg (Table 2). During the 2 years of below average precipitation (2021 and 2022) daily NO_3^--N load averaged 3.1 kg for the control ditch whereas the treatment ditch averaged 1.7 kg (Table 1). During the 2 years of above average precipitation (2018 and 2019) daily NO_3^--N load averaged 9.1 kg and 6.6 kg for the control and treatment, respectively (Table 1). During the 3 years of average precipitation (2017, 2020, and 2023) daily NO_3^--N averaged 8.5 kg and 6.0 kg for the control and treatment ditches, respectively (Table 1). These data showed that, regardless of the climatic cycle, the treatment ditch with the low-grade weir always attenuated NO_3^--N load. The data also indicated that NO_3^--N load from the treatment ditch was lowest under dry conditions, intermediate under average conditions, and highest under wet conditions.

There was a statistically significant monthly effect of NO_3^--N load primarily related to periods of high, intermediate, and low flow (Table 3). Monthly distribution and magnitude of control ditch NO_3^--N losses from 2017 to 2023 is found in Figure 5A. Over the this period, at no time was monthly NO_3^--N loss from the treatment channel greater than the control channel. Overall, this figure shows that the greatest NO_3^--N losses occurred during the 2-month period, April and May. Ditch NO_3^--N losses also steadily declined between June and August. Nitrate losses began to increase in September in years when autumn precipitation recharged soil water content.

Monthly distribution and magnitude of ditch NO_3^--N losses from 2017 to 2023 for the treatment ditch containing the low-grade weir appear in Figure 5B. Overall, this figure shows that monthly distribution of ditch NO_3^--N losses from the treatment ditch was similar to that of the control ditch. In contrast, the magnitude of the treatment ditch NO_3^--N losses for all months were lower than those from the control ditch. Nitrate losses were lowest on average in August. A combination of lower flows and higher temperatures during summer is generally conducive to higher rates of microbial activity, including denitrification. These data suggest that use of weirs can provide enhanced hydrological residence time in these systems, and thus promote conditions conducive for nitrogen removal via denitrification to occur.

Above average annual precipitation resulted in greater NO_3^--N loads during to two wet years, 2018 and 2019. Nitrate-N losses were recorded in every month between April and October during 2018. On an annual basis, NO_3^--N loss was greater for the control channel, 1,544 kg compared to 930 kg for the treatment channel during 2018. The implementation of the low-weir in the treatment channel resulted in an overall reduction in NO_3^--N loss of 40% for the treatment channel compared to the control channel.

Nitrate-N losses were recorded in every month between March and October during 2019. Similar to 2018, on an annual basis, NO_3^--N loss was greater for the control channel, 2,307 kg compared to the treatment channel, 746 kg, during 2019. The maximum monthly NO_3^--N load occurred during April 2019 in the control channel. Above-average precipitation in late August and September resulted in an increase in NO_3^--N loss for both channels although the magnitude of the increase was smaller for the treatment ditch (Figures 5A, B). During August, ditch channels reached their lowest observed NO_3^--N losses of the growing season. This result is not unexpected as corn and soybean were vigorously growing at this point actively taking up water and nutrients.

Below average annual precipitation resulted in the smallest NO_3^--N loads during 2021 and 2022. During 2021, the first dry year of consecutive dry years, NO_3^--N losses were recorded in March and then September to December. On an annual basis, NO_3^--N loss was greater for the control channel, 183 kg compared to 146 kg for the treatment channel during 2021. During 2022, the second year of consecutive dry years, NO_3^--N losses were recorded in March through July. On an annual basis, NO_3^--N loss was greater for the control channel, 660 kg compared to 318 kg for the treatment channel during 2022. The implementation of the low-grade weir in the treatment channel resulted in an overall reduction in NO_3^--N loss of 52% compared to the control channel.

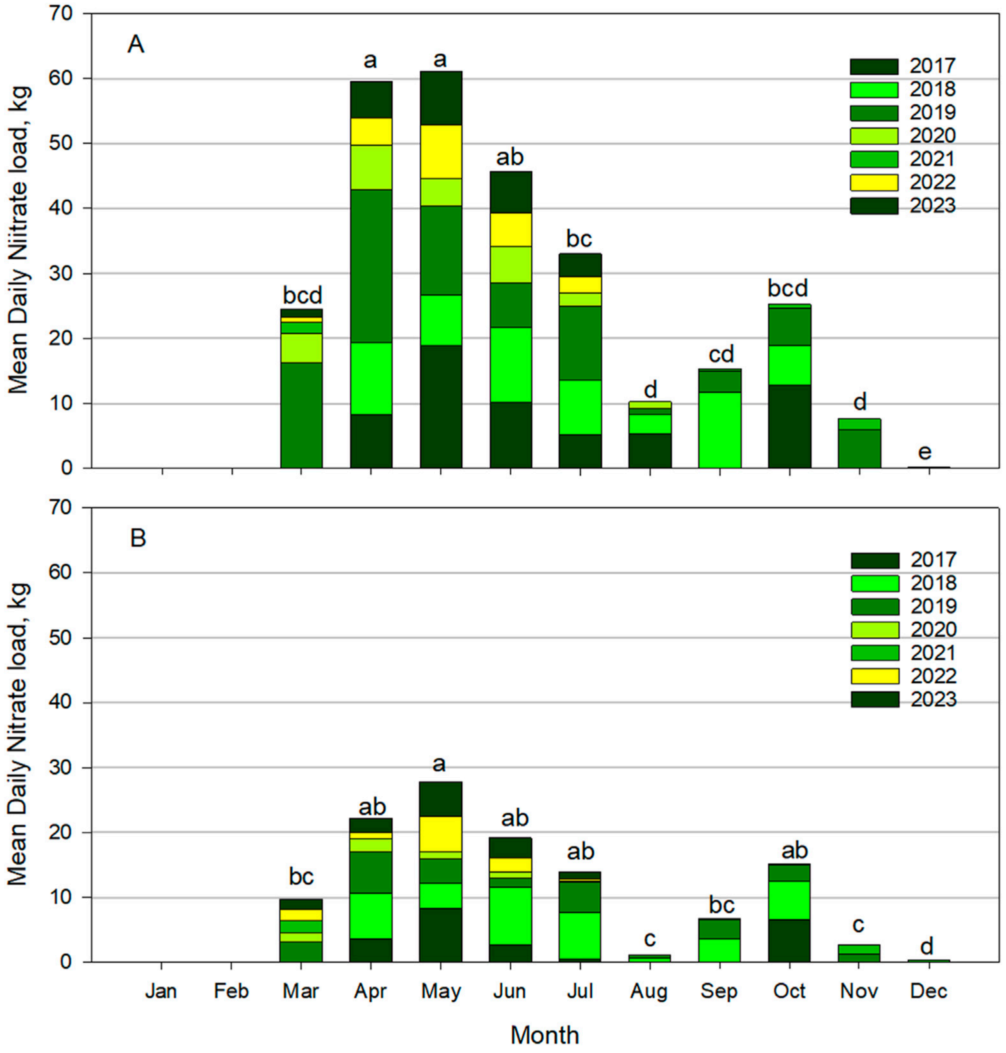

FIGURE 5
Monthly control **(A)** and treatment **(B)** ditch nitrate-load between January and December. Means followed by the same lowercase letter are not significantly different at $P \leq 0.10$.

The largest monthly loss of NO_3^--N in 2022 occurred during May when 245 kg was exported from the control ditch.

Average annual precipitation resulted in intermediate NO_3^--N loss during the 3 years, 2017, 2020 and 2023. On average, NO_3^--N loss was greater for the control channel, 1,041 kg compared to 391 kg for the treatment channel during these 3 years. The implementation of the low-grade weir in the treatment channel resulted in an overall reduction in NO_3^--N loss of 62% compared to the control channel.

4 Discussion

Annual variation in nutrient losses including NO_3^--N loss from drained agricultural landscapes has been primarily attributed to the volume of water exported through subsurface drainage (Gramlich et al., 2018). Subsurface drainage is influenced by the frequency, intensity, and distribution of precipitation over time and the amount of annual or monthly precipitation that occurs. Previous research has also shown that NO_3^--N concentration can be affected by dry and wet climatic conditions (Randall and Goss, 2008; Duncan et al., 2017). Based on the results from this experiment, it was evident that the presence of low-grade weirs in the treatment ditch affected NO_3^--N concentration.

The current experiment showed reductions in discharge and FWMNC from the treatment compared to the control ditch. In contrast, results reported from research conducted in the Lower Mississippi River Valley showed no difference in NO_3^--N concentration in systems with or without low-grade weirs (Kröger et al., 2012). Variations in ditch FWMNC observed in this study show that concentration does not depend solely on ditch discharge. Ditch NO_3^- concentrations are also an indication of nitrogen source, storage, and transport as well as biologically mediated processes such as microbial uptake, vegetation uptake, nitrification, and denitrification. Recent work on N dynamics in southern Manitoba demonstrated that high concentrations of inorganic N were associated with snowmelt runoff, while summer inorganic N concentrations remained consistently low, suggesting increased biological N transformation and N removal (Friesen-

Hughes et al., 2021). In addition, shifts in temperature across seasons, vegetation phenology, and subsurface drainage discharge periods could all impact FWMNC.

The overall reduction in NO_3^--N loss from the treatment channel indicated that the low-grade weir increased residence time in the ditch and this coupled with a larger wetted perimeter and deeper channel behind the low-grade weir likely resulted in denitrification. Recent studies have demonstrated the capacity of managed agricultural drainage ditches to mitigate N (Kröger et al., 2007; Kröger et al., 2012; Littlejohn et al., 2014). In these studies, the authors reported a wide range in NO_3^--N load reductions ranging from 14% to 66%. The authors ascribed the differences to shortened HRT attributed high flows. The current study demonstrated similar load reductions only under different climate conditions. Although not specifically measured, denitrification would be expected to be the main driver of NO_3^--N reduction in the treatment channel although uptake into emergent vegetation also likely occurred as air temperatures increased and vegetation matured. Increased HRT and increased area inundation under the ditch containing the low-grade weir system was hypothesized to have increased denitrification potential and as a result the potential for higher reductions in NO_3^--N load for treatment ditch compared to the control ditch.

Another possible explanation for NO_3^--N loss differences between the channels could be that one or both channels were influenced by shallow groundwater. Ditch channel-groundwater interactions in which a ditch channel gained water from shallow groundwater could appear to decrease NO_3^--N loss resulting result from a possible dilution effect of shallow groundwater with a lower NO_3^--N concentration than the ditch channel. In addition, seepage losses from a ditch channel to shallow groundwater could result in an apparent decrease in NO_3^--N loss from ditch channels. This phenomenon was observed by researchers in southern France (Dagès et al., 2008). The authors suggested that contaminants such as NO_3^--N would be confined to the wetted perimeter of ditches, and that its transmission to the deeper groundwater would occur very slowly or that it would return in some measure to the ditch flow if the water table were to rise above the water level in the ditch during a runoff event. The authors further suggested that groundwater contamination in catchments with dense ditch networks would be difficult to monitor both spatially and temporally (Dagès et al., 2008).

Excess water and droughts create *hot moments* and *hot spots* as distinct temporal and spatial components of biogeochemical responses. Excess water has a dominating effect on the export of dissolved nutrients from agricultural landscapes. Nitrate-nitrogen retention efficiency decreases with increasing flow (Wollheim et al., 2017). High flows generated by seasonal snowmelt or rainfall events mobilize large pulses of nutrients (e.g., Pellerin et al., 2012). Increased water depth and velocity during high flows reduces reactive capacity by decreasing HRT available for biogeochemical processing (Basu et al., 2011).

In contrast, low-flow periods such as droughts are potentially dominant control points for biogeochemical processing, enhancing variation in nutrient concentrations, metabolism, and nutrient uptake. For example, shifts in environmental conditions because of hydrologic pulsing could have an impact on ditch microorganism presence, abundance, and function. In a recent study, a ditch with low-grade weirs achieved 60% higher NO_3-N removal compared to an unmanaged ditch during low flow conditions (Wang et al., 2024). The authors attributed the reduction most likely to N removal by denitrification or another anerobic N removal process.

Low-grade weirs should be considered as BMPs for nitrogen removal in source agricultural landscapes, as they promote conditions conducive for NO_3-N reduction through denitrification (Kröger et al., 2014). Evaluation of weirs in this study under cold climate conditions and other research suggests that ditches managed with low-grade weirs increase HRT (Kröger et al., 2008) as well as decrease NO_3^--N concentrations and loads over drainage ditches that do not have any water management structures (Kröger et al., 2011). The process of nitrogen removal from agricultural drainage is dependent on microbial denitrification (Tank et al., 2021). Denitrification has been studied in systems used to treat agricultural drainage. In a study in Minnesota, the researchers found a significantly greater abundance of 16S rRNA gene and genes associated with denitrification (nirK, nirS, norB, and nosZ) in a ditch managed with a low-grade weir compared to an unmanaged ditch (Wang et al., 2024). In contrast, in a 3-year study aimed at understanding the effects of low-grade weirs on soil microbial communities in agricultural drainage ditches in Mississippi the researchers found no significant differences between sites with and without low-grade weirs (Baker et al., 2018). These disparities with the current study could be in part due to differences in ditch geometry, characteristics, management, and duration of treatment. For example, in the Mississippi study the researchers used rip-rap weirs which were only in place for 3 years. We hypothesize that ditch conditions may not have stabilized under this short length of time, thus the microbiome may not have had sufficient time for ditch conditions to come to the same level of stability as those in the present study (i.e. 17 years).

Nitrate removal performance within drainage ditches equipped with low-grade weirs has been shown to be effective at reducing NO_3-N load by 25%–67% with greater reductions observed under low-flow conditions (Littlejohn et al., 2014). Previous research in Indiana showed that two-stage ditches offer the potential to reduce NO_3-N concentrations, but NO_3-N load was observed to increase by 2% (Hodaj et al., 2017). In contrast, two-stage ditch research in Minnesota showed a NO_3-N load reduction range between 14% and 34% (Krider et al., 2022). In a review of the performance of denitrifying bioreactors for treatment of NO_3-N from agricultural drainage water the authors reported a mean (± standard deviation) NO_3-N load reduction of 40% ± 26% (Christianson et al., 2021). In a review of the performance of saturated buffers for treatment of NO_3-N from agricultural drainage water the authors reported a mean (± standard deviation) NO_3-N load reduction of 46% ± 24% (Johnson et al., 2023).

Our research demonstrated the potential benefits of using low-grade weirs as a management tool in drainage ditches at cold latitudes. However, the potential benefit of managing ditches with low-grade weirs is variable dependent on growing season precipitation. In addition, this experiment was conducted with only one weir in place over the entire length of the ditch as well as only two inflow sources of water. Along the length of public and private ditches there are many inflow sources of drainage water. The water quality and quantity impact of multiple inflow sources of water and their occurrence at irregular intervals is a knowledge gap. Moreover, low-grade weirs are currently manually operated.

Frequently adjusting low-grade weirs during the flow season is not practical unless the management process is automated. A more responsive management of low-grade is necessary for adjusting the drainage intensity during periods of low flow to high flow depending on timing and amount of precipitation, and subsequently optimizing the benefits of low-grade weirs. With the recent advances in sensor technologies, weather forecast, data acquisition, transmission, and analytics, the automation of low-grade weirs seems feasible.

5 Conclusion

The purpose of this research was to advance fundamental changes in agricultural drainage ditch management from the existing paradigm of ditch management that focuses on water conveyance, requiring periodic ditch maintenance (clean out) which shortens HRT and removes valuable carbon supplies (vegetation), drastically limiting nutrient cycling, especially N; to a new paradigm where ditches are managed using minimally invasive low-grade weirs to temporarily store water on the landscape to help mitigate peak flows and reduce nutrient losses from agricultural landscapes. Ditches are a common means of conveying excess drainage water from agricultural land in in the Midwest. These ditches are necessary for maintaining strong agricultural production, but they have the potential to lead to loading of excess nutrients to surface waters. Agricultural best management practices such as filter strips, conservation tillage and nutrient and residue management planning are currently practiced to minimizing agricultural impacts on water quantity and quality. However, other approaches such as minimally invasive ditch management of water flow, vegetation, and/or management of the ditch geometry have the potential to further help agricultural and environmental managers protect our nations water resources.

Overall ditch management was quite effective in mitigating discharge and nitrogen loss from runoff and drainage water. State and federal mandates for nitrogen reduction to the Gulf of Mexico for Minnesota are the same, a 45% reduction by 2045. To meet this goal practices like low-grade weirs in drainage ditches should be considered given that this experiment, with significant variation in annual precipitation amounts, indicates that on average, the installation of low-grade weirs in drainage ditches can reduce nitrate loss by 61%, 16% above the current mandate level. In addition, this style of management of ditch drainage water is minimally invasive and does not require additional agricultural land be taken out of production. Although two-stage ditches have been shown to have positive impacts on mitigating nutrients from agricultural production they are expensive to build and take valuable crop land out of production.

Ditches are complex systems with characteristics of headwater streams and wetlands. Designing and applying ditch management practices that address nonpoint source agricultural pollution problems will be beneficial in the implementation of water quality protection programs and achieving state and federal nutrient reduction goals.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing–original draft, Writing–review and editing. AR: Data curation, Formal Analysis, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The researcher’s time was supported in part by the Hatch capacity grant program, from the U.S. Department of Agriculture’s National Institute of Food and Agriculture.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

References

Baker, B. H., Brooks, J. P., Deng, D. D., Smith, R. K., Kröger, R., and Czarnecki, J. M. P. (2018). Effects of low-grade weirs on soil microbial communities in agricultural drainage ditches. *J. Environ. Qual.* 47, 1155–1162. doi:10.2134/jeq2017.12.0489

Basu, N. B., Thompson, S. E., and Rao, P. S. C. (2011). Hydrologic and biogeochemical functioning of intensively managed catchments: A synthesis of top-down analyses. *Water. Resour. Res.* 47 (10). doi:10.1029/2011wr010800

Birgand, F., Skaggs, R. W., Chescheir, G. M., and Gilliam, J. W. (2007). Nitrogen removal in streams of agricultural catchments—a literature review. *Crit. Rev. Environ. Sci. Technol.* 37 (5), 381–487. doi:10.1080/10643380600966426

Christianson, L. E., Cooke, R. A., Hay, C. H., Helmers, M. J., Feyereisen, G. W., Ranaivoson, A. Z., et al. (2021). Effectiveness of denitrifying bioreactors on water pollutant reduction from agricultural areas. *Trans. Am. Soc. Agric. Biol. Eng.* 64 (2), 641–658. doi:10.13031/trans.14011

Dagès, C., Voltz, M., Lacas, J., Huttel, O., Negro, S., and Louchart, X. (2008). An experimental study of water table recharge by seepage losses from a ditch with intermittent flow. *Hydrol. Process.* 22 (18), 3555–3563. doi:10.1002/hyp.6958

Duncan, J. M., Welty, C., Kemper, J. T., Groffman, P. M., and Band, L. E. (2017). Dynamics of nitrate concentration discharge patterns in an urban watershed. *Water Resour. Res.* 53, 7349–7365. doi:10.1002/2017WR020500

Durand, P., Breuer, L., Johnes, P. J., Billen, G., Butturini, A., Pinay, G., et al. (2011). “Nitrogen processes in aquatic ecosystems,” in *European nitrogen assessment* M. A. Sutton and C. M. Erisman Cambridge: Cambridge University Press, 126–146. Available at: https://centaur.reading.ac.uk/20855/.

Evans, R., Skaggs, R. W., and Gilliam, J. W. (1995). Controlled versus conventional drainage effects on water quality. *J. Irrigation Drainage Eng.* 121 (4), 271–276. doi:10.1061/(asce)0733-9437(1995)121:4(271)

Faust, D., Kröger, R., Moore, M., and Rush, S. (2018). Management practices used in agricultural drainage ditches to reduce Gulf of Mexico hypoxia. *Bull. Environ. Contam. Toxicol.* 100, 32–40. doi:10.1007/s00128-017-2231-2

Fennel, K., and Laurent, A. (2018). N and P as ultimate and proximate limiting nutrients in the northern Gulf of Mexico: implications for hypoxia reduction strategies. *Biogeosciences* 15 (10), 3121–3131. doi:10.5194/bg-15-3121-2018

Friesen-Hughes, K., Casson, N., and Wilson, H. (2021). Nitrogen dynamics and nitrogen-to-phosphorus stoichiometry in cold region agricultural streams. *J. Environ. Qual.* 50 (3), 653–666. doi:10.1002/jeq2.20234

Gramlich, A., Stoll, S., Stamm, C., Walter, T., and Prasuhn, V. (2018). Effects of artificial land drainage on hydrology, nutrient and pesticide fluxes from agricultural fields–A review. *Agric. Ecosyst. and Environ.* 266, 84–99. doi:10.1016/j.agee.2018.04.005

Hodaj, A., Bowling, L. C., Frankenberger, J. R., and Chaubey, I. (2017). Impact of a two-stage ditch on channel water quality. *Agric. Water Manag.* 192, 126–137. doi:10.1016/j.agwat.2017.07.006

JMP (2019). *JMP, Version 15.0*. Cary, NC: SAS Institute Inc.

Johnson, G., Christianson, L., Christianson, R., Davis, M., Díaz-García, C., Groh, T., et al. (2023). Effectiveness of saturated buffers on water pollutant reduction from agricultural drainage. *J. Nat. Resour. Agric. Ecosyst.* 1 (1), 49–62. doi:10.13031/jnrae.15516

Kaur, G., Zurweller, B. A., Nelson, K. A., Motavalli, P. P., and Dudenhoeffer, C. J. (2017). Soil waterlogging and nitrogen fertilizer management effects on corn and soybean yields. *Agron. J.* 109, 97–106. doi:10.2134/agronj2016.07.0411

Krider, L., Kramer, G., Wilson, B., Magner, J., Lazarus, W., Hansen, B., et al. (2022). Alternative agricultural ditch designs, NO3-N treatment, construction costs, and benefits—mower county, Minnesota, USA. *J. Environ. Sci. Eng. B* 11, 229–240. doi:10.17265/2162-5263/2022.06.002

Kröger, R., Cooper, C., and Moore, M. (2007). A preliminary study of an alternative controlled drainage strategy in surface drainage ditches: low-grade weirs. *Agric. Water Manag.* 95, 678–684. doi:10.1016/j.agwat.2008.01.006

Kröger, R., Cooper, C., and Moore, M. (2008). A preliminary study of an alternative controlled drainage strategy in surface drainage ditches: low-grade weirs. *Agric. Water Manag.* 95, 678–684. doi:10.1016/j.agwat.2008.01.006

Kröger, R., Moore, M., Farris, J., and Gopalan, M. (2011). Evidence for the use of low-grade weirs in drainage ditches to improve nutrient reductions from agriculture. *Water Air Soil Pollut.* 221, 223–234. doi:10.1007/s11270-011-0785-x

Kröger, R., Pierce, S. C., Littlejohn, K. A., Moore, M. T., and Farris, J. L. (2012). Decreasing nitrate-N loads to coastal ecosystems with innovative drainage management strategies in agricultural landscapes: an experimental approach. *Agric. Water Manag.* 103, 162–166. doi:10.1016/j.agwat.2011.11.009

Kröger, R., Scott, J., and Prince Czarnecki, J. (2014). Denitrification potential of low-grade weirs and agricultural drainage ditch sediments in the lower Mississippi Alluvial Valley. *Ecol. Eng.* 73, 168–175. doi:10.1016/j.ecoleng.2014.09.019

Li, Y., Guan, K., Schnitkey, G. D., DeLucia, E., and Peng, B. (2019). Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Glob. change Biol.* 25 (7), 2325–2337. doi:10.1111/gcb.14628

Littlejohn, K., Poganski, B., Kröger, R., and Ramirez-Avila, J. (2014). Effectiveness of low-grade weirs for nutrient removal in an agricultural landscape in the Lower Mississippi Alluvial Valley. *Agric. Water Manag.* 131, 79–86. doi:10.1016/j.agwat.2013.09.001

Martin, E., Godwin, I., Cooper, R., Aryal, N., Reba, M., and Bouldin, J. (2021). Assessing the impact of vegetative cover within Northeast Arkansas agricultural ditches on sediment and nutrient loads. *Agric. Ecosyst. Environ.* 320, 107613. doi:10.1016/j.agee.2021.107613

Moore, M. T., Cooper, C. M., and Farris, J. L. (2005). “Drainage ditches,” in *Water encyclopedia*. Editors J. Lehr, J. Keeley, J. Lehr, and T. B. Kingery (New York, NY: John Wiley and Sons, Inc.).

Nifong, R. L., Taylor, J. M., and Moore, M. T. (2019). Mulch-derived organic carbon stimulates high denitrification fluxes from agricultural ditch sediments. *J. Environ. Qual.* 48, 476–484. doi:10.2134/jeq2018.09.0341

Olson, K., Morton, L., and Speidel, D. (2016). Little river drainage district conversion of big swamp to fertile agricultural land. *J. Soil Water Conservation* 71 (2), 37a–43A. doi:10.2489/jswc.71.2.37a

Pellerin, B. A., Saraceno, J. F., Shanley, J. B., Sebestyen, S. D., Aiken, G. R., Wollheim, W. M., et al. (2012). Taking the pulse of snowmelt: in situ sensors reveal seasonal, event and diurnal patterns of nitrate and dissolved organic matter variability in an upland forest stream. *Biogeochemistry* 108, 183–198. doi:10.1007/s10533-011-9589-8

Rabalais, N. N., and Turner, R. E. (2019). Gulf of Mexico hypoxia: past, present, and future. *Limnol. Oceanogr. Bull.* 28 (4), 117–124. doi:10.1002/lob.10351

Randall, G. W., and Goss, M. J. (2008). “Nitrate losses to surface water through subsurface, tile drainage,” in *Nitrogen in the environment: sources, problems, and management*. Editors J. L. Hatfield and R. F. Follett (Elsevier Inc).

Reinhart, B. D., Frankenberger, J. R., Hay, C. H., and Helmers, M. J. (2019). Simulated water quality and irrigation benefits from drainage water recycling at two tile-drained sites in the US Midwest. *Agric. Water Manag.* 223, 105699. doi:10.1016/j.agwat.2019.105699

Strock, J. S., Sands, G. R., Krebs, D. J., and Surprenant, C. (2005). Design and testing of a paired drainage channel research facility. *Appl. Eng. Agric.* 21 (1), 63–69. doi:10.13031/2013.17914

Tank, J. L., Speir, S. L., Sethna, L. R., and Royer, T. V. (2021). The case for studying highly modified agricultural streams: farming for biogeochemical insights. *Limnol. Oceanogr. Bull.* 30, 41–47. doi:10.1002/lob.10436

USDA National Agricultural Statistics Service (USDA-NASS) (2017). 2017 census of agriculture – United States data. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/st99_1_0047_0047.pdf.

Wang, H., Strock, J., Ranaivoson, A., and Ishii, S. (2024). Bioremediation of nitrate in agricultural drainage ditches: Impacts of low-grade weirs on microbiomes and nitrogen cycle gene abundance. *Sci. Total. Environ.* 955, 177070. doi:10.1016/j.scitotenv.2024.177070

Williams, M. R., King, K. W., and Fausey, N. R. (2015). Contribution of tile drains to basin discharge and nitrogen export in a headwater agricultural watershed. *Agric. Water Manag.* 158, 42–50. doi:10.1016/j.agwat.2015.04.009

Wollheim, W. M., Mulukutla, G. K., Cook, C., and Carey, R. O. (2017). Aquatic nitrate retention at river network scales across flow conditions determined using nested in situ sensors. *Resour. Res.* 53, 9740–9756. doi:10.1002/2017wr020644