SUBSURFACE NITRATE PROCESSING BENEATH DRAINAGEWAYS: ARE THEY LANDSCAPE OPPORTUNITIES FOR SUBSURFACE DRAINAGE REMEDIATION?

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HIGHLIGHTS

- Drainageways contain fine-textured and nutrient rich alluvial soils conducive for denitrification.
- NO_3-N concentrations in drainageway groundwater were 70% lower than observed in cropped fields.
- A new grass waterway design connects subsurface water from upland cropped fields to the drainageway deposits for NO_3-N remediation.

ABSTRACT. *Efforts to reduce nutrient export from agricultural crop production in the U.S. Midwest are leading to development of new conservation practices. In this study our objectives were to: (1) characterize subsurface soils and hydrogeology found in two main drainageway areas in eastern Iowa, (2) compare groundwater quality to upland agricultural fields, and (3) utilize a groundwater flow model to assess the capacity of drainageways to provide additional NO_3-N processing in agricultural watersheds. Using data obtained from a network of 12 shallow wells installed across six different waterways, we found that the waterways contained fine-textured and nutrient rich alluvial soils derived from erosion and deposition of upland loess and till. Concentrations of NO_3-N in waterway groundwater (3.1 mg/l) were 70% lower compared to groundwater beneath nearby cropped fields (10.5 mg/l). A shallow water table in the organic-rich drainageway soils provides the requisite organic carbon, anaerobic soil conditions, and nitrogen supply for denitrification to occur. Numerical modeling suggested that groundwater from the surrounding catchment discharges approximately 53 m^3/day into the waterways and reduces NO_3-N mass by 144.3 kg/yr, or 7.8 kg/ha. Results suggest that drainageways could be better exploited for additional NO_3-N reductions from subsurface drainage if the flow could be diverted into these areas.*

Keywords. *Denitrification, Grass waterway, Nitrate-nitrogen, Saturated buffer.*

Efforts to reduce nutrient transport from agricultural crop production in the U.S. Midwest are leading to the development of new conservation practices such as blind inlets (Smith and Livingston, 2013), prairie filter strips (Zhou et al., 2014), multipurpose oxbows (Schilling et al., 2019), and saturated buffers (Jaynes and Isenhart, 2014). Newer conservation practices are often focused on enhancing nutrient processing within the existing agricultural systems where water quality benefits can be achieved with minimal impacts on crop production (Schulte et al., 2006). Herein, we highlight how there may be potential to capitalize on additional nutrient processing using an established conservation practice.

In the dissected glacial landscape of North America beyond the extent of Wisconsin glaciation (fig. 1), thick-to-thin wind-blown silt (loess) overlies weathered glacial till. Topography in the region is characterized by rolling hills and a well-developed drainage network of interconnected swales, drainageways, streams, and rivers (Schilling et al., 2013). Upland soils eroded from the loess and glacial till fill the drainageways with fine-textured alluvium. Grass waterways are a common conservation practice used in drainageways to reduce gully soil erosion in rolling agricultural landscapes. Sod-based grasses planted as grass waterways slow concentrated surface water runoff from agricultural hillslopes and reduce soil erosion (Li et al., 2016; Dermisis et al., 2010; Fiener and Auerswald, 2003; Meyer et al., 1999). Runoff volume was found to be reduced by 47% in grassed waterways compared to non-grassed waterways in one study (Briggs et al., 1999). Another study showed that grass waterways reduced the runoff volume by only 5%, but peak runoff rates were reduced by 54% (Hjelmfelt and Wang, 1999). Runoff is reduced when water is slowed and it

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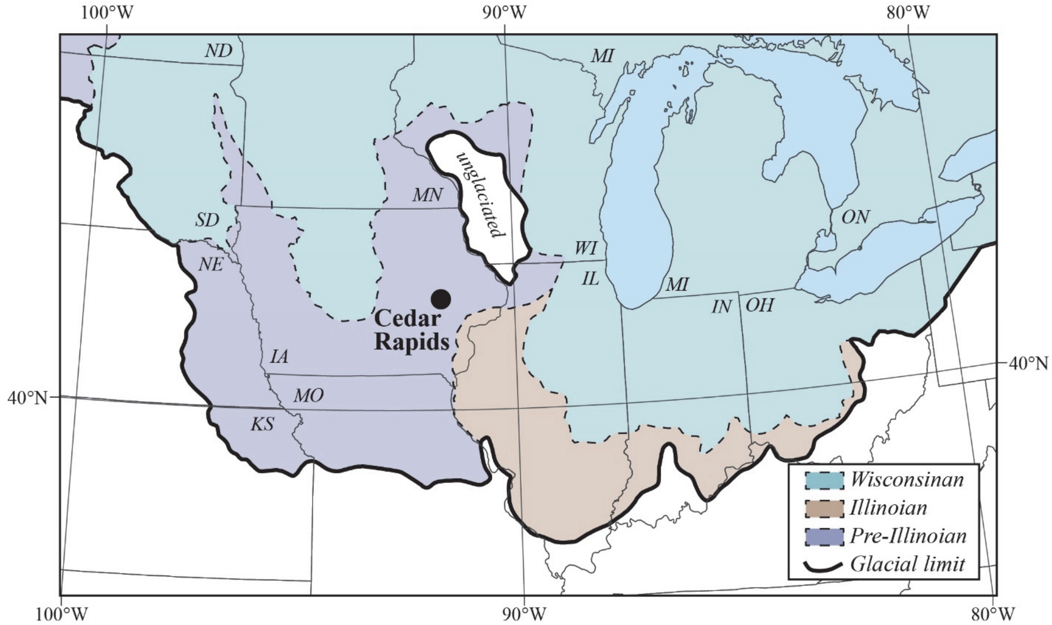

Figure 1. Extent of Quaternary glaciations in the north-central USA. Location of Cedar Rapids and study location at Kirkwood Community College. Results from this study apply to the dissected glacial landscapes associated with Pre-Illinoian and Illinoian glaciations.

infiltrates into the waterway soils and most of the research conducted on grass waterway practices has focused on their role in reducing soil erosion from surface water runoff. They are often planted with sod-forming grasses which reduce runoff, sediment transport, and gully formation by slowing water flow. These grass systems absorb significant dissolved and sediment bound nutrients in runoff (Dermisis et al., 2010). As a surface erosion prevention practice, the benefits of grass waterways are well understood.

However, the subsurface characteristics and potential nutrient reduction benefits of grass waterway systems have not been well investigated. Research by Schilling et al. (2007) and Schilling et al. (2013) in the Walnut Creek watershed in south-central Iowa indicated that drainageways in first-order catchments often contain accumulations of saturated, organic-rich Holocene-age alluvium capable of denitrifying groundwater NO_3-N. Schilling et al. (2007) reported that NO_3-N concentrations in a 7.6 ha catchment decreased from 10 mg/l in upland row crop areas to <0.5 mg/l in the drainageway. A groundwater contaminant transport model was used to suggest that the drainageway sediments could process all the upland groundwater NO_3-N flowing through them. Schilling et al. (2013) compared the drainageway conditions found in the 1st-order drainageway to riparian conditions along the 3rd-order main channel and noted that the stratigraphy and hydrologic conditions were very similar in both areas of the watershed. The authors considered these areas to be "natural bioreactors" that provide enhanced biochemical processing of NO_3-N. However, beyond these studies, there has been little follow-up work to determine whether subsurface conditions found in southern Iowa extend to other regions of the state. Grass waterways continue to be viewed, first and foremost, as a practice designed to reduce surface water erosion and they have not been explored adequately as a potential location for subsurface NO_3-N processing.

In this study, we evaluated the subsurface soils and hydrogeology found in two drainageway areas in eastern Iowa and assessed the potential for nitrate processing to occur in these lowland environments. Our study objectives were to: (1) characterize geologic and groundwater conditions within drainageways, (2) compare results to comparable monitoring being performed in upland agricultural fields nearby, (3) estimate catchment-scale nitrate reduction using a groundwater flow model, and (4) assess the capacity of landscape to provide additional NO_3-N processing in the larger agricultural landscape. Since most grass waterways are designed to include subsurface drainage to reduce soil wetness and prevent the formation gullies (NRCS, 2014), our study explored how these subsurface waterway deposits could be used for future drainage remediation in the glaciated Midwest.

Methods and Materials

Study Area

Our study focused on waterways located in two main areas south of Cedar Rapids in Linn County, Iowa (fig. 2). The eastern site is located on property owned and managed by Kirkwood Community College (Kirkwood). Kirkwood maintains the largest community college agricultural program in the U.S. and operates a 325 ha diversified farm as part of its educational program. The western site is located on farmland owned by the College Community School District that is leased to a local farmer. Both fields are managed under two-year corn and soybean rotations and drain toward Hoosier Creek, a third-order stream that flows approximately 10 km east before discharging to the Coralville Reservoir on the Iowa River. The waterway vegetation mainly consists of cool-season smooth brome (*Bromus inermis*).

The Hoosier Creek watershed is representative of the Southern Iowa Drift Plain landscape region of Iowa, an area characterized by rolling hills and a well-developed drainage

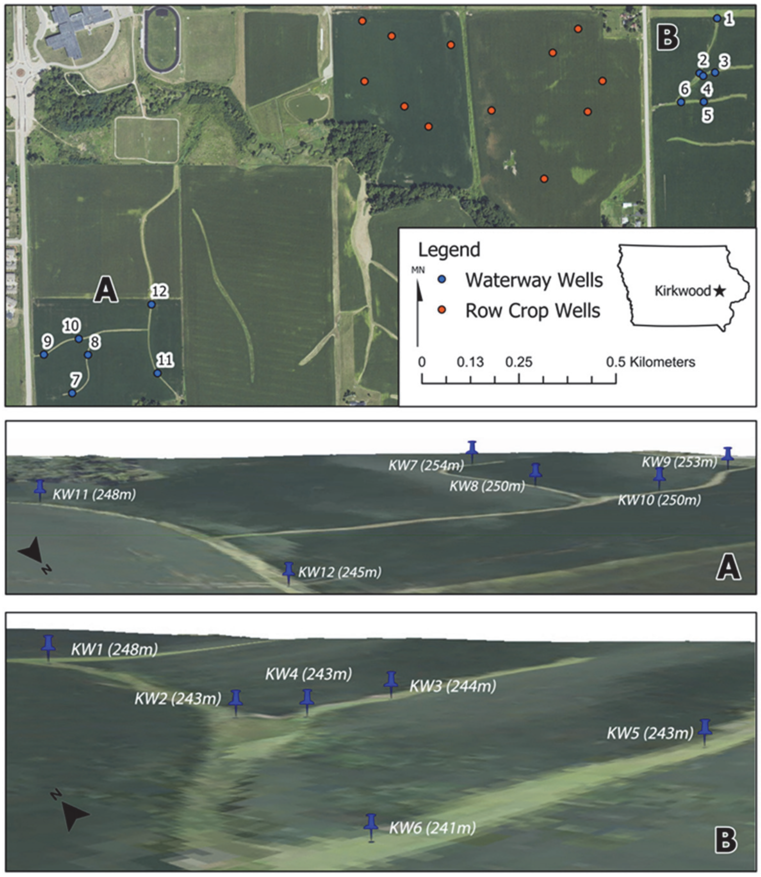

Figure 2. Location of drainageway and upland cropped field wells at Kirkwood Community College farm site. In inset maps A and B, an oblique view of the watersheds shows the well numbers (KW11) and land surface elevation of the well site in meters above seas level (248m).

system (Prior, 1991). Upland areas are typically dominated by 2 to 6 m of oxidized and leached silt loam (Wisconsin loess) that mantles loamy and dense pre-Illinoian glacial till, whereas the lowland drainageways largely consist of fine-textured alluvium derived from the erosion of upland loess and till. Several studies have shown that the alluvial fill deposits in loess-mantled areas of the Midwest share a similar depositional history and contain mappable stratigraphic deposits across the region (Bettis et al., 1992; Baker et al., 2002).

Field Investigation

Twelve shallow monitoring wells were installed at upslope and downslope positions within different portions of the waterways in the two main study areas (fig. 2). All wells were installed using a hand auger or Giddings drilling rig. The 3.8 cm diameter wells were installed to a uniform depth of 2.1 m and consisted of a 1.5 m well screen and a 1.5 m riser that extended the well above the land surface. A graded sand filter pack was poured around the screen and bentonite chips were added to provide a seal. Following well installation, the wells were developed by surging and overpumping using a Waterra sampling system. Two wells in each waterway area instrumented with a Level TROLL transducer (30 psi, In-Situ, Inc) to measure hourly water table fluctuations. Regional precipitation data were downloaded from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/).

Soil samples were collected from well locations to gather information about soil morphological properties at the sites. Soil samples were characterized according to methods of (Schoeneberger et al., 2012). Soils samples were air-dried and ground to pass through a 2 mm sieve for particle size and elemental analysis. Soil texture was determined by x-ray absorption using a Sedigraph® (Olivier et al., 1971). Elemental analysis via chromatography was performed following dry combustion to measure total carbon (TC) and total nitrogen (TN).

Due to landowner concerns, we were not able to monitor groundwater immediately upgradient of the waterways. However, results from a concurrent investigation of upland groundwater conditions within the Kirkwood farm area allowed us to compare groundwater conditions in two landscape settings within the same local vicinity. Twelve monitoring wells were installed using the Giddings rig in two 80-ac parcels under corn and soybean rotations (fig. 2). The 3.8 cm diameter wells were installed to a depth of 4.5 m and consisted of a 3 m well screen and a 1.5 m riser that extended the well above the land surface. The wells were completed and developed using the same procedures as the waterway wells. A Level TROLL transducer (30 psi, In-Situ, Inc) was installed in well KM4 to measure hourly water table fluctuations.

Both the drainageway and upland cropped wells were sampled on the same days approximately biweekly from April to November 2020 (16 occasions). Water levels in wells were measured to the nearest 0.01 foot (0.3 cm) at the time of sampling. Water samples were collected using a peristaltic pump and analyzed in the field for temperature, specific conductance (SC), pH, dissolved oxygen (DO), and oxidation-reduction potential (ORP) using a YSI ProDSS water quality meter. Samples to be analyzed for NO_3-N, chloride (Cl), and sulfate (SO_4) were collected in polyethylene bottles. Samples to be analyzed for dissolved reactive phosphorus (DRP) were filtered in the field immediately upon collection through a 0.45 µm filter into a 60 mL acid-washed brown glass bottle. All samples were immediately stored in a cooler at 4 °C until they could be transported back to the laboratory and refrigerated. Samples were typically analyzed within 24 hours of sampling.

Laboratory Analysis

Concentrations of NO_3-N, Cl, and SO_4 were measured using a Dionex ICS-1000 ion chromatograph equipped with an AS-14A 5µm ion exchange column, an AS-14A guard column, an AMMS-III or AERS 500 suppressor, and $Na2CO_3/NaHCO_3$ eluent. A Dionex autosampler (AS40) was utilized with autosampler vials fitted with 20 µm filter caps. Dissolved reactive orthophosphate (DRP) was analyzed using a Lachat QuikChem 8500 Series 2 flow injection analyzer running Lachat method 10-115-01-1-P.7 All glassware used in sampling and analysis of DRP was acid washed in 1 M hydrochloric acid.

Data Analyses

Water data were summarized as means and standard deviation for each sample location. Water levels were summarized as hourly means. Groundwater concentrations were summarized as means and standard deviations in individual wells and by landscape classification (drainageway vs row crop field). All water data comparisons were made using analysis of variance using Minitab (Release 18).

Groundwater Model

To estimate groundwater flow from the catchment to the waterway and N load reductions, we developed a three-dimensional groundwater flow model for the western waterway area using Visual MODFLOW Flex Version v.7.0 (Waterloo Hydogeologic, Inc., 2021). A two-layer model was used for the simulation. Layer 1 represented 3-m thick upland loess and alluvium with a horizontal hydraulic conductivity of 0.2 meters/day, consistent with slug tests and typical for loamy soil conditions. Layer 2 represented a 12-m thick confining silty clay (oxidized glacial till) with a horizontal hydraulic conductivity of 0.04 meters/day (Schilling and Tassier-Surine, 2006). Vertical hydraulic conductivity was estimated to be 1/10 the horizontal hydraulic conductivity in both layers. The ratio is consistent with local hydrogeologic conditions where the geometric mean hydraulic conductivity in unoxidized till was shown to be more than two orders of magnitude lower than overlying oxidized and fractured till (Schilling and Tassier-Surine, 2006). Average groundwater recharge over the 18.6 ha model domain was 139 mm/yr (Schilling et al., 2021), although less recharge was modeled (46 mm/year) in the SE upland area of the model. The local catchment divide was considered a no-flow boundary. The MODFLOW Drain Package was used to quantify water flux from the drainageways. The drain was set to 3 meters deep and to an average width of 8 meters.

Results

Subsurface Characterization of Waterway Deposits

The geology of the two drainageway areas was evaluated using lithologic observations and physical analyses and we compiled physical and chemical soil data and grouped them by landscape position (table 1). The parent materials for the three landscape positions differed from loess to pedisediment and alluvium, and this was reflected in different soil classifications as soil units transitioned from Kenyon/Dinsdale to Colo. Typical of alluvial fill derived from erosion of upland loess and till, the subsurface deposits at all three positions were dominated by silt and clay (79 to 88%), with slightly more sand present in the mid- and footslope locations. Higher long-term water tables in the footslope areas are indicated by a shallower depth to gleying/mottling, with the average gleying depth systematically decreasing from 124 cm in the upland part of the drainageway to 22 cm in the footslope.

The footslope position in the waterways contained a thicker A horizon and (86±38 cm) and more total carbon (TC) (1.51±0.25%) than the other landscape positions (table 1). Total nitrogen (TN) was similar at the three regions, but with higher TC values; C:N ratios were observed to increase downslope in the waterways. Overall, assuming an average width of 6 m and bulk density of 1.25 g/cm^3, the stock of carbon in the waterways more than doubled from approximately 34-45 kg/m of waterway in the upland and midslope locations to nearly 100 kg/m in the footslope position (table 1).

Table 1. Summary of soil properties measured at drainageway wells.

Landscape position	Upland	Midslope	Footslope
Wells used in study	1, 7, 9	2, 3, 4, 5, 10, 11	6, 8, 12
Average Depth of A Horizon (cm)	47±8	32±9	86±38
Depth to gleying/mottling (cm)	124±39	98±50	22±8
Sand (%)	13±3	20±2	19±3
Silt (%)	58±2	50±2	52±3
Clay (%)	30±1	29±1	29±1
TC (%)	1.27±0.24	1.43±0.18	1.51±0.25
TN (%)	0.12±0.02	0.12±0.01	0.11±0.02
C:N	8±1	11±1	12±1
TC in A Horizon (kg/m of waterway)[a]	45	34	97
Parent Material	Loess	Loess/Pedisediment/Pre-Illinoian till	Pedisediment/Holocene Alluvium
Profile Classification	Kenyon/Dinsdal	Kenyon/Floyd/Klinger/Dinsdale	Colo

[a] carbon stock assumes a waterway width of 6 m and a bulk density of 1.25g/m^3.

HYDROLOGY

Precipitation was not measured at the site, but annual precipitation in 2020 measured at the Cedar Rapids municipal airport (10 km west) totaled 927 mm. The annual total was similar to the long-term average for the region which is approximately 905 mm (https://www.weather.gov).

Water table depths were measured continuously from approximately April to November in up- and downgradient wells in a waterway (fig. 3). Water table levels closely followed similar temporal pattern and largely fluctuated between 0.5 to 1 m below ground surface, rapidly responding to precipitation inputs. Water table depths at other study wells were measured at the time of sampling (n=16 per well [table 2]). The average water table depth ranged from approximately 0.45 to 1.0 m below ground surface and averaged 0.77 m among all wells. The water table was typically higher in the downgradient wells compared to the corresponding upgradient well in the waterway. Based on slug tests, the hydraulic conductivity of the fine-textured alluvium averaged approximately 0.02 m/day in the waterway wells.

A groundwater flow model was constructed for the southeast waterway area (fig. 4). The hydraulic head at the individual wells was determined by subtracting the water table depth from the land surface elevation. Model hydraulic heads were compared to measured values in the waterway wells and the normalized root mean square error was 4.8% (fig. 5). As expected, groundwater in the catchment follows local topography and flows into the waterway areas from the surrounding upland (fig. 3). Model results suggested that groundwater from the catchment under steady-state conditions discharges approximately 52.7 m^3/day into the waterways within the boundaries of the farm field.

WATER QUALITY

Water samples were collected biweekly from 12 monitoring wells on 16 occasions from March to November in 2020 and mean concentrations and standard deviations are provided in table 2. Mean NO_3-N concentrations ranged from 0.7 to 9.8 mg/l among the wells, although all but one well had mean concentrations <3.5 mg/l. Concentrations fluctuated throughout the year in response to precipitation recharge,

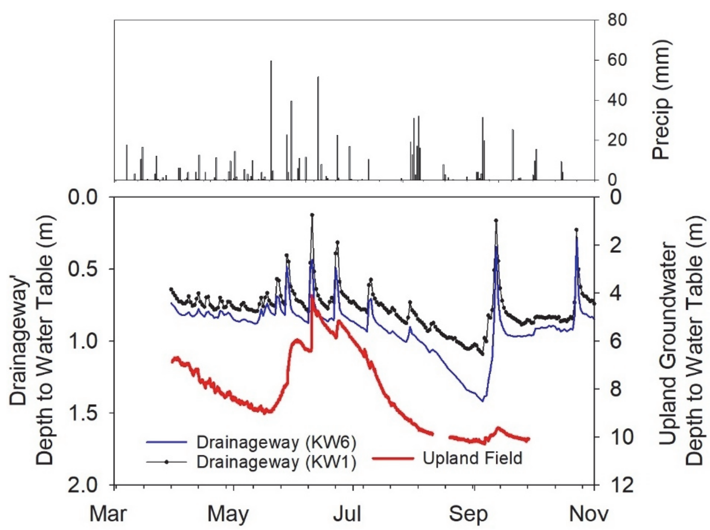

Figure 3. Precipitation and water table depths measured in representative drainageway wells in 2020. Water table depths measured in upland cropped field are plotted on the secondary y-axis.

Table 2. Summary of water quality monitoring results in waterway wells (mean ± 1 standard deviation for 16 samples per well). For cropped field, results are summarized for the population of 12 wells ((mean ± 1 standard deviation for 12 wells x 16 samples).[a]

Waterway Wells	DTW (m)	Temp (°C)	pH	Spec. Cond. (µS/cm)	DO (mg/l)	ORP (mV)	NO_3-N (mg/l)	DRP (mg/l)	Cl (mg/l)	SO_4 (mg/l)
KW1	0.78 ± 0.10	12.8 ± 12.4	7.3 ± 1.8	469 ± 68	3.2 ± 0.8	92 ± 60	3.1 ± 2.5	0.15 ± 0.16	12.6 ± 3.3	9.2 ± 2.7
KW2	0.72 ± 0.21	14.4 ± 9.7	7.2 ± 1.9	547 ± 49	3 ± 0.6	118 ± 54	1.3 ± 1.8	0.09 ± 0.06	14.3 ± 3.9	16.9 ± 4.2
KW3	0.58 ± 0.23	14.8 ± 9.7	7.3 ± 1.8	500 ± 74	3.4 ± 0.9	108 ± 57	1.9 ± 1.5	0.26 ± 0.24	23.6 ± 10.5	10.3 ± 3.6
KW4	1.05 ± 0.20	14.1 ± 9.5	7.4 ± 1.9	494 ± 87	3.6 ± 1.3	122 ± 50	1 ± 0.9	0.16 ± 0.26	14.2 ± 6.4	10.7 ± 3.3
KW5	0.82 ± 0.37	14.9 ± 10	7.4 ± 2	568 ± 80	3.5 ± 1	121 ± 50	3.3 ± 1.6	0.12 ± 0.20	21.7 ± 5.1	17.4 ± 5.6
KW6	0.91 ± 0.14	15.1 ± 9.7	7.2 ± 2	527 ± 43	3.2 ± 0.5	126 ± 40	2.7 ± 0.9	0.08 ± 0.06	16.7 ± 3.6	15.4 ± 2.9
KW7	1.05 ± 0.44	14.3 ± 9.6	7.2 ± 1.9	532 ± 86	3.4 ± 1.3	123 ± 64	3.5 ± 3.9	0.27 ± 0.27	19.1 ± 4.4	19.9 ± 5.1
KW8	0.49 ± 0.38	14.5 ± 9.4	7.3 ± 1.8	558 ± 40	3.8 ± 0.9	119 ± 66	9.8 ± 2.2	0.16 ± 0.19	14.2 ± 2.5	10.2 ± 1.5
KW9	0.98 ± 0.54	14.8 ± 9.4	7.3 ± 2	1044 ± 293	4.7 ± 1.3	135 ± 69	1.1 ± 0.8	0.11 ± 0.12	134.1 ± 64.7	20.3 ± 7.2
KW10	0.70 ± 0.38	12.7 ± 11.9	7.5 ± 1.8	628 ± 224	3.7 ± 1.5	112 ± 69	0.9 ± 0.8	0.17 ± 0.15	61.4 ± 23.6	18 ± 7.6
KW11	0.842± 0.17	14.9 ± 9.3	7.4 ± 1.9	679 ± 16	3.8 ± 1.2	123 ± 51	3.4 ± 1.3	0.08 ± 0.04	24.6 ± 4.8	21.7 ± 4.7
KW12	0.60 ± 0.15	12.3 ± 12.4	7.3 ± 2	608 ± 83	3.4 ± 0.7	111 ± 42	0.7 ± 0.4	0.18 ± 0.24	22 ± 8.1	18.4 ± 5.8
Upland Cropped Field Wells (12 total)	2.15 ± 1.35	16.6 ± 3.9	6.9 ± 1.5	532 ± 187	6.34 ±2.3	133 ± 54	10.5 ± 6.2	0.11 ± 0.19	15 ± 5.0	15.6 ± 7.2

[a] DTW=depth to water table; Temp = temperature; Spec Cond = specific conductance, DO = dissolved oxygen, ORP = oxidation reduction potential; DRP = dissolved reactive phosphorus

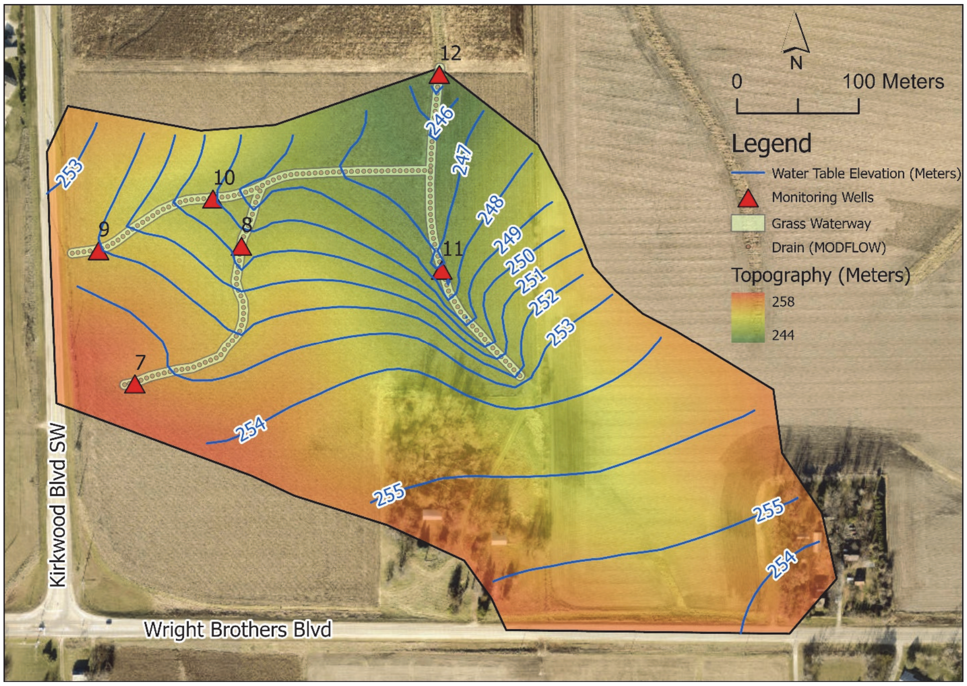

Figure 4. Model domain and simulated hydraulic heads for the eastern drainageway catchment.

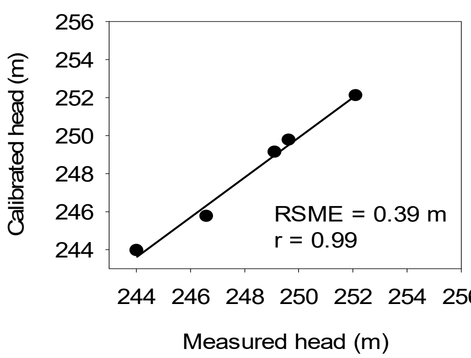

Figure 5. Relation of measured mean annual hydraulic head in monitoring wells calibrated to hydraulic head values from steady-state MODFLOW groundwater model. Well 7 (see fig. 4) was inactivated because the measured water levels were near the bottom of the well screen and it would go dry during model calibration.

although the temporal patterns seemed to vary among the sites (fig. 4). Peak NO_3-N concentrations were measured in mid-June in KW1/KW2 and KW7 but were higher in mid-August in KW3/KW4 and KW5/KW6. Overall, NO_3-N concentrations were considerably lower in well pairs KW9-KW10 and downgradient well KW12 (<1.1 mg/l). However, concentrations measured in KW8 were anomalously high during the year. It is important to note that the waterways receive groundwater nutrient inputs from upland areas all along their downslope linear extent and upland loads contribute to NO_3-N levels found in the waterways. Therefore, the upgradient-downgradient concentration patterns in the waterways would not be expected to show the same behavior. Overall, for all wells and all dates, NO_3-N concentrations averaged 3.1 mg/l in waterway groundwater.

Mean groundwater DRP concentrations ranged from approximately 0.08 to 0.26 mg/l among the wells (table 2), with an overall waterway mean concentration of 0.16 mg/l. Higher values were observed in well KW3 (range 0.03 to 0.86 mg/l), but most wells exhibited a relatively narrow range of concentrations. Chloride concentrations exhibited wide variability and appeared to be influenced by road salt impacts in the western portion of the west waterway where Cl concentrations exceeded 100 mg/l. Elsewhere, Cl and SO_4 concentrations fluctuated within a relatively narrow range (13 to 25 mg/l; 9 to 22 mg/l; respectively) (table 2).

Comparison of Waterway Conditions to Upland Cropped Fields

Groundwater conditions in upland cropped fields were markedly different than those monitored in the waterways. The water table was deeper beneath the upland fields; for example, in well KM4 the water table fluctuated nearly 6 m in response to seasonal precipitation recharge and evapotranspiration losses (fig. 3). Groundwater NO_3-N concentrations in the uplands were significantly higher than values measured in the waterways ($p<0.01$) (fig. 7), averaging 3.1 mg/l in the waterways and 10.5 mg/l in the cropped fields (table 2). We used the groundwater flux from the numerical flow model to estimate the annual NO3-N load entering the southeast waterway area. Assuming that upland groundwater was discharging NO_3-N concentrations of 10.6 mg/l into the waterways (fig. 3), approximately 203.9 kg of NO_3-N load enters the waterway per year. With an average waterway NO_3-N concentration of 3.1 mg/l, the waterway exports approximately 59.6 kg/yr of NO_3-N. This represents a NO_3-N mass reduction of 144.3 kg/yr in the waterway sediments, or an N load reduction of 7.8 kg/ha based on the 18.6 ha contributing catchment area.

In contrast to NO_3-N, mean DRP concentrations were higher in the waterways than in the cropped fields (0.16 vs 0.11 mg/l, respectively) (fig. 6) but the difference was not statistically significant ($p=0.06$). Cl concentrations (excluding

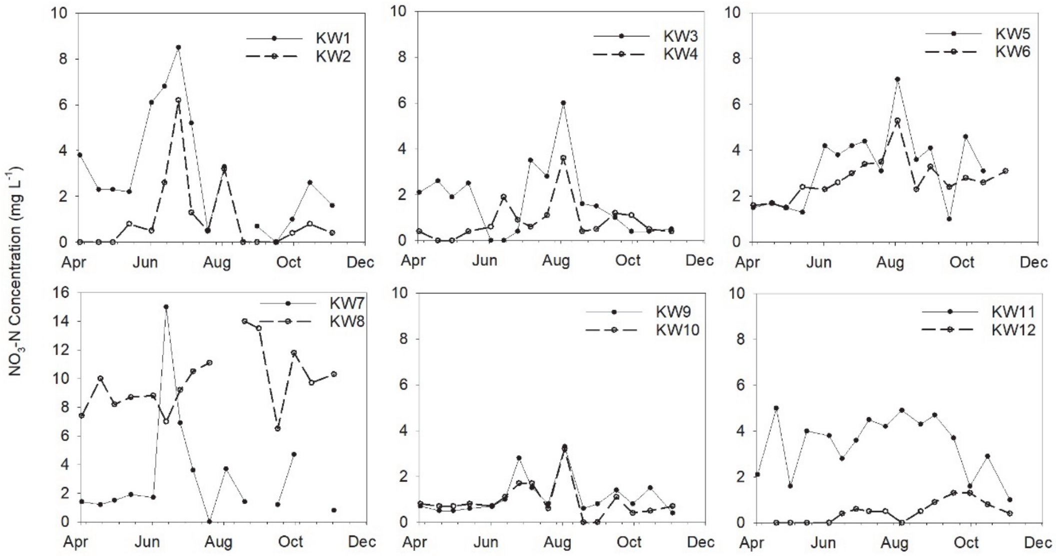

Figure 6. Temporal patterns of groundwater NO_3-N concentrations measured in upslope and downslope wells installed in drainageways.

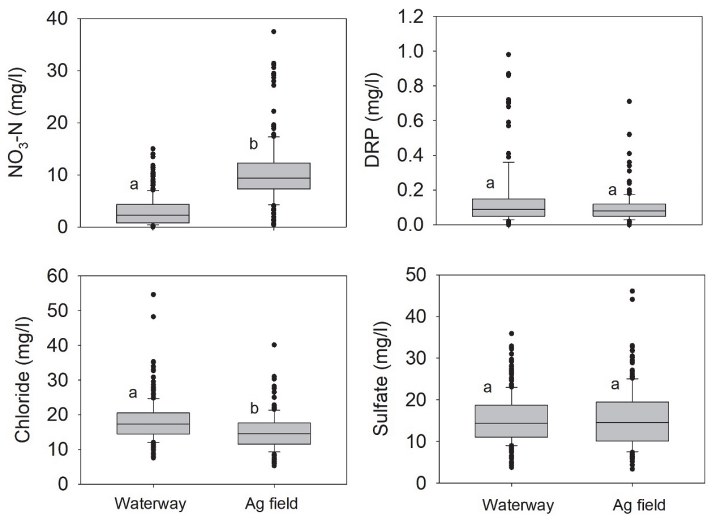

Figure 7. Comparisons of groundwater quality beneath the drainageways to conditions in nearby agricultural row crop fields. Letters denote significant differences ($p<0.05$).

wells KW9 and KW10) were slightly higher in the waterways ($p<0.05$), whereas there was not significant difference in SO_4 concentrations ($p>0.1$). In-field water analyses were completed immediately upon the extraction of water samples (table 2). DO concentrations varied only slightly within the wells ranging from 3.0 to 4.7 mg/l, with an overall waterway average of 3.5 mg/l. Consistent with NO_3-N concentrations, DO was significantly higher (6.5 mg/l) in the upland row crop fields compared to the waterways ($p<0.001$). ORP and pH values were relatively stable in the waterways, ranging between 92 to 135 mv and 7.2 to 7.4, respectively. SC ranged from 468 to 679 mS/m in most wells and was considerably higher in the road salt impacted well KW9 (1,044 mS/m).

DISCUSSION

NO_3-N Processing in Drainageway Deposits

Consistent with previous work focused in south-central Iowa (Schilling et al., 2007, 2013), soil and groundwater conditions in eastern Iowa drainageway are favorable for subsurface processing of NO_3-N. These lowland areas within the rolling glacial landscape are natural repositories for organic sediments eroded from surrounding hillslopes and are uniquely positioned in the landscape to maintain wetness and receive inputs of N from the surrounding hillsides.

The topography and sequence of glacial deposits found at the eastern Iowa sites are typical of the pre-Wisconsin glacial extent where uplands are underlain by oxidized and leached silt loams (typically loess) and dense glacial till (Schilling and Tassier-Surine, 2006). Loess and glacial till eroded from the uplands and slopes are deposited as fine-textured alluvium in drainageways and riparian zones. At the eastern Iowa waterway sites, soils were dominantly fine-textured (79 to 88% silt and clay) and contained abundant TN and TC contents reflective of upland agricultural soils (Schilling et al., 2013). Accumulation of organic materials was evidenced in the waterways with the downslope stock of TC increasing from approximately 40 to nearly 100 kg of

TC per m of waterway (table 1). In non-calcareous soils, like those in the waterways of our study, soil organic matter (SOM) may be assumed to be approximately double TC (Konen et al., 2002). SOM levels were estimated to be approximately 3% in the waterways (double that of the measured TC content of the waterway soils (1.51±0.25%) and was well above the minimum requirement of 1.2% recommended for saturated buffers (Chandrasoma et al., 2019).

Although we were not able to document groundwater quality immediately upgradient of the waterway wells, there was a clear difference in shallow groundwater quality beneath active row crop fields nearby and in the waterways. NO_3-N concentrations averaged 10.5 mg/l beneath nearby cropped fields and 3.1 mg/l in the waterways, which represents an average concentration reduction of approximately 70%. Consistent with studies of Iowa saturated buffers (Groh et al., 2019; Jaynes and Isenhart 2014, 2019), we believe that denitrification is primarily responsible for the N concentration reductions. The waterways contain the conditions considered to be needed for denitrification to occur, including sufficient organic carbon, anaerobic conditions, and a steady nitrogen supply (e.g., Burt et al., 1999; Cey et al., 1999; Clément et al., 2002; Kellogg et al., 2010). The high water tables in the waterways, averaging <0.8 m below ground surface, keeps nitrogen-rich groundwater in close contact with organic-rich alluvium and plant roots and microbes to provide carbon as an electron donor (Gold et al., 2001; Hefting et al., 2004).

Groundwater DO concentrations were low (~2-4 mg/l) and redox conditions were <120 mv. Denitrification primarily occurs in settings with DO concentrations less than 2 mg/l (Cey et al. 1999) and redox conditions less than 200 mv (Anderson, 2004) and the groundwater conditions in the waterways appear to be suitable, but not necessarily ideal for potential denitrification. Since the waterways are linear features in the landscape, they are hydrologically open systems that receive subsurface flow from the uplands along their entire extent. Hence, upland groundwater continually replenishes DO in the waterway and likely maintains higher DO and NO_3-N in the waterways. Nonetheless, groundwater conditions in the waterways are similar to conditions found within bioreactors where DO concentrations have been measured between 1 to 4 mg/l in controlled environments (Martin et al., 2019). We hypothesize that denitrification is occurring primarily in small microenvironments where DO has been depleted and reducing conditions are maintained (Jacinthe et al., 1998). It is recognized that N cycling among forms occurs in subsurface environments and the processes driving these cycles include mineralization, nitrification, and immobilization (e.g., Guo et al., 2014; Gomez-Rey et al., 2012; Booth et al., 2005). In particular, nitrification typically occurs at DO concentrations above 3 mg/l (Sharma and Ahlert, 1977), and this, in addition to upland groundwater contributions, may account for the incomplete removal of NO_3-N in the waterway sediments.

Groundwater flow modeling of the southeast waterway area (fig. 3) suggested that the waterway sediments reduced inflow NO_3-N loads from the surrounding uplands by 144.3 kg/yr. This magnitude of annual N load reduction is similar to reductions measured in Iowa saturated buffers (13 to 179 kg N reported by Jaynes and Isenhart, 2019; 75 to 136 kg N reported by Streeter and Schilling, 2021) and restored oxbows that receive tile drainage (100 to 400 kg/yr; Schilling et al., 2019). The N mass load reductions among these practices are comparable because edge of field practices often treat very similar catchment areas (i.e., 20 to 80 ac; Schilling et al., 2019). Likewise, the N load reduction based on the contributing area in this study (7.8 kg/ha) was similar to the load reductions of saturated buffers (3.2 to 11 kg/ha (Jaynes and Isenhart, 2019). Hence, the waterway sediments appear to be functioning as a natural "saturated buffer" to reduce groundwater N concentrations and loads from upland cropped areas.

Overall, the hydrogeology and water quality patterns observed in Linn County (eastern Iowa) waterways are remarkably consistent with conditions observed in south-central Iowa (Schilling et al., 2007) and attest to the regional nature of the observations. Throughout the glaciated Midwest, erosion of upland loess and till has led to the deposition of nutrient-enriched alluvium in low-order drainageways. We contend that the simple landscape model of stratigraphy, groundwater flow, and NO_3-N concentration reductions is applicable to much of the loess-mantled extent of glaciation across the Corn Belt of the US.

DRP

In contrast to NO_3-N, average waterway groundwater DRP concentrations (0.16 mg/l) were higher than concentrations monitored under currently cropped fields (0.11 mg/l). Although the difference was not statistically significant ($p=0.06$), it is worth noting that high water tables in the waterway and the mildly anaerobic geochemical environment may encourage the release of Fe-bound P from soils (Tomer et al., 2010; Carlyle and Hill, 2001). In addition, mineralization of organic P may also be influencing OP concentrations (Reddy et al., 1999; Carlyle and Hill, 2001). Overall, groundwater DRP concentrations in drainageways are similar to concentrations measured in a variety of settings across Iowa (Schilling et al., 2020).

Implications

Subsurface drainage is a recommended grass waterway design practice because it prevents long-term buildup of excessive wetness, maintains the vegetative cover, prevents formation of gullies, and facilitates accessibility of farm equipment into fields (NRCS, 2014; USDA, 2007). The USDA Engineering Field Handbook, Part 650 (2007) recommends that subsurface drains should be considered in waterways where wet conditions are prolonged and states that, "subsurface drains should parallel the center of the vegetated waterway but be offset from the centerline at least a fourth of the top width of the waterway. Two drains may be required in some cases, one on each side of the center." Tiling beneath drainageways results in groundwater NO_3-N concentrations bypassing possible denitrification, thereby increasing water and N export from the landscape.

We believe that the existing grass waterway conservation practice could be modified to exploit the N processing drainageway deposits. Just like saturated buffers are constructed to reconnect tile drainage water to the riparian buffer for N reduction (Jaynes and Isenhart, 2014), subsurface drainage in grass waterways could be altered to reconnect upland groundwater to the organic-rich drainageway deposits for NO_3-N reduction. Regional geologic mapping indicates that most drainageways in the area are filled with saturated and organic-rich alluvium, and more research is needed to assess the ability of the waterways to process the excess water that might be delivered to them. Grass waterways are an extremely common conservation practice in rolling cropped landscapes in the dissected glacial landscape.

To illustrate this, we used the Agricultural Conservation Planning Framework (ACPF) (Tomer et al., 2015), to identify grass waterway locations in the Hoosier Creek watershed where similar suitable drainageway conditions are likely to be encountered. In the 91-km^2 watershed, the ACPF identified 826 potential grass waterway sites (fig. 8). Assuming that the 826 waterways could reduce NO3-N at a similar rate as this study (144 kg/year), the waterways could conceivably reduce N loads in Hoosier Creek by approximately 119,000 kg/year. To put this in perspective, we used the averaged water export in Hoosier Creek (334 mm) and assumed an average NO_3-N concentration of 10 mg/l to estimate a total export load of 303,940 kg NO_3-N. Hence, the waterways could be capable of reducing N loads exported from Hoosier Creek by approximately 39% if they were not drained. Overall, the high number of potential locations suggests that modifying the grass waterway conservation practice to exploit potential N load reductions available in the waterway sediments could potentially reduce NO_3-N export from the basin.

STUDY LIMITATIONS

We recognize that our study of drainageways in eastern Iowa has limitations. First, our study was conducted for one year, and this timeframe may not be sufficient to account for climatic and agricultural management variations. Hydraulic heads and nutrient concentrations measured in wells could vary based on seasonal drought or wet conditions (Jones et al., 2018) or due to crop type or fertilizer applications (Hatfield et al., 2009). However, water and nutrient transport through fine-textured soils and groundwater can be slow in many agricultural systems (Rodvang and Simpkins, 2001) and we assumed that the drainageway conditions monitored for one year reflect long-term average conditions. This assumption is reasonable because the topography of the catchments controls the hydraulic head and drives groundwater flow from the uplands to the drainageways. This hydrogeologic setting will maintain a high water table in the drainageway deposits despite climate variability. Likewise, the sedimentological properties of the drainageway sediments are the product of centuries of development and will be largely unchanged by recent agricultural management. The consistent behavior of the groundwater system was further demonstrated by continuous water level monitoring and sampling on 16 occasions over one field season, showing minimal temporal variations among two sites during a growing season. Hence, the one-year timeframe was sufficient to document the spatial patterns of sediment and hydrology in two drainageways.

A second limitation of this study was not having upland and drainageway wells within the same study catchments. A network of wells within the same catchment would have more definitely linked the hydrology and groundwater quality from upland areas to the drainageways. However, field researchers are aware of the challenges in getting monitoring wells installed within privately-owned cropped fields and we were fortunate to have in-field wells installed in other cropped fields within the Kirkwood farm area. We assumed that water table patterns and nutrient concentrations measured in upland cropped fields managed by the same producer would provide similar results.

Lastly, we assumed that field and modeled conditions monitored at two drainageways near Kirkwood could be extrapolated to the larger Hoosier Creek watershed and beyond. The estimated N load reduction from the groundwater flow model utilized field data consistent with regional information (Schilling and Tassier-Surine, 2006). Although water and nutrient yields from the catchment would be expected to

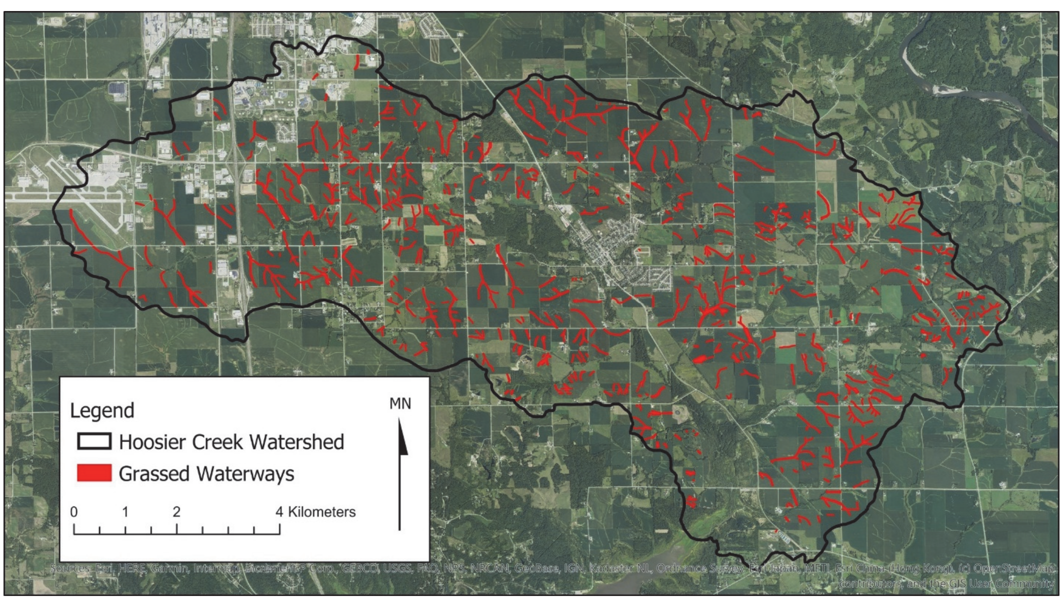

Figure 8. Potential locations of similar drainageway sediments in Hoosier Creek watershed estimated using the ACPF tool.

vary to some degree based on annual and seasonal climate, we modeled a steady-state condition that was based on spatial (not temporal) patterns. Transient simulations could be done in the future to test how well the steady-state model captured seasonal or annual patterns. Extending the results from this study to the entire Hoosier Creek watershed and to the dissected glacial landscape of the Midwest is possible because the drainageway deposits are a product of a shared erosion and depositional history across the region. The sediment and hydrology conditions in eastern Iowa are remarkably consistent with those encountered in southern Iowa (Schilling et al., 2007) and attest to the regional similarity. We would expect that other catchments in the dissected glacial Midwest with similar upland loess over till stratigraphy would have analogous saturated and organic-rich drainageway deposits.

Conclusions

In this study, we evaluated two drainageway areas in eastern Iowa to assess their potential for reducing subsurface NO_3-N. Using monitoring results from a network of 12 shallow wells installed across six different waterways, we found that the lowland drainageways contained fine-textured and nutrient rich alluvial soils derived from erosion and deposition of upland loess and till. Strong circumstantial evidence, including a high water table, abundant organic carbon, anaerobic conditions, and an ongoing nitrogen source, suggested that conditions within the waterways were conducive for denitrification to occur and we observed that NO_3-N concentrations in waterway groundwater (3.1 mg/l) were 70% lower than observed in groundwater beneath cropped fields (10.5 mg/l). Groundwater flow modeling suggested that the waterways sediments removed approximately 144 kg N per year, or 7.8 kg/ha based on the contributing area, values that are very similar to N reductions measured in saturated buffers. Grass waterways are a common conservation practice in rolling cropped landscapes and results from this study suggest that they could be exploited for additional NO_3-N reductions from subsurface drainage if flow could be diverted into these areas. Naturally occurring sediments in the drainageways could provide additional N processing of subsurface drainage water in the agricultural Midwest.

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