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Effectiveness of natural riparian buffers to reduce subsurface nutrient losses to incised streams

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ABSTRACT

Perennial vegetation borders many incised, perennial streams and rivers in southern Iowa and is assumed to provide a natural riparian buffer against subsurface nutrient losses from shallow groundwater. Questions remain about the effectiveness of these systems near incised channels that cut through nutrient-rich Holocene alluvium underlying the riparian corridors. In this study, riparian groundwater nutrient concentrations were evaluated near an incised stream under four perennial land cover types common to southern Iowa with the objectives to assess how groundwater quality differed by i) distance away from an incised stream and ii) perennial land cover type. Groundwater samples were collected from riparian wells installed 1 m, 20 m and 40 m from an incised channel under four replicated land covers (cool season grass, warm season grass, woods, pasture) on six occasions across the growing season. Results indicate that channel incision lowers water tables in the near-stream zone and maintains more aerobic conditions but did not result in enhanced nitrogen mineralization or leaching to groundwater. Average concentrations of nitrate–nitrogen, phosphorus and dissolved organic carbon were 0.3 mg/l, 0.2 mg/l and 6 mg/l, respectively, with variations due mainly to land cover type and geomorphology. Study results suggest that nutrient losses from perennial buffers in the region do not greatly impact regional water N and P loads although average concentrations in riparian groundwater may exceed proposed stream nutrient criteria.

1. Introduction

Establishing perennial vegetation adjacent to a stream is considered to be an effective best management practice (BMP) to buffer aquatic ecosystems against nutrient losses from groundwater (Phillips, 1989; Schultz et al., 1995; Spruill, 2000). Such riparian buffers attenuate nitrogen through plant uptake (Lowrance, 1992), denitrification (Clement et al., 2003; Jacobs and Gilliam, 1985), and groundwater mixing (Altman and Parizek, 1995; Lowrance et al., 1997). Less well documented are effects of riparian vegetation on groundwater concentrations of phosphorus (Carlyle and Hill, 2001) and dissolved organic carbon (DOC) (Jacinthe et al., 2003).

Comparing the effectiveness of different riparian zone configurations is often complicated by variations in vegetation type and subsurface geology that occur among sites. The influence of different vegetation types on riparian buffer performance has largely centered on evaluating nutrient processing at a single vegetated site, such as forests (Lowrance, 1992; Peterjohn and Correll, 1984), grasslands (Borin and Bignon, 2002; Schoonover and Williard, 2003) or forest–grassland combinations (Addy et al., 1999; Haycock and Pinay, 1993). Mayer et al. (2005) used a meta-analysis to suggest that forest was more effective than grass in nitrogen removal effectiveness. Additional studies of riparian buffer effectiveness have focused on systems established under USDA conservation standards (Dosskey, 2001). Moreover, variations in subsurface lithology and stratigraphy often play a critical role in controlling nutrient cycling and transport in riparian zones (DeVito et al., 2000; Hill et al., 2004). Mittelstet et al. (2011) showed that groundwater phosphorus contributions to streams can be significant when riparian soils exhibit spatial variability in hydraulic conductivity and preferential flow pathways. Studies are needed to evaluate natural buffers that control for subsurface geologic variability so that effectiveness of riparian vegetation type on groundwater quality can be better quantified.

Further complicating comparisons of riparian buffer effectiveness across sites is the effect of channel incision on shallow groundwater quality (Schilling and Jacobson, 2008). Agricultural practices such as stream channelization, removal of riparian vegetation, increasing row crop production and widespread artificial drainage have caused many streams to downcut and widen into their floodplains. Incised streams are hydrologically disconnected from their floodplains, lowering the water table near the stream and creating a large unsaturated zone in the near-stream riparian zone (Hardison et al., 2009; Schilling et al., 2004). Deeper water tables near incised channels can result in a more aerobic soil profile conducive for mineralization of soil N (Groffman et al., 2002; Schilling and Jacobson, 2008).

In this study, we evaluated groundwater nutrient concentrations in riparian wells installed near an incised stream under four perennial

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land cover types common to southern Iowa. Naturally occurring remnant forests and herbaceous communities line many kilometers of incised streams in this region yet little is known about their ecological effectiveness (Knight et al., 2011). For example, in northern Missouri (the same ecoregion as much of southern Iowa), Herring et al. (2006) found that riparian land use consisted of forest (46%), cropland (29%) or grass (23%). Evaluating groundwater nutrient concentrations beneath naturally occurring perennial riparian buffers is critical since these buffers overlie nutrient-rich Holocene-age alluvium. Recent work in southern Iowa indicated that nitrogen and carbon contents can range up to 0.42% and 7.1%, respectively, and phosphorus concentrations up to 1792 mg/kg in fine-grained alluvium (Schilling et al., 2009). The ability of natural perennial buffers to control nutrient losses to streams incising through the Holocene alluvium has not been assessed.

The purpose of this study was to examine how groundwater nutrient concentrations varied in the riparian zone of an incised stream. In particular we were interested in evaluating factors that affect groundwater concentration patterns, namely i) distance away from an incised stream and ii) perennial land cover type, with our ultimate objective being to assess the effectiveness of natural riparian buffers to reduce nutrient losses to incised streams in southern Iowa. Our study follows previous work by Schilling et al. (2009) that focused on nutrient concentrations in riparian soils. Herein we test the implication posed by the earlier study that high nutrient concentrations in riparian soils will adversely impact the quality of groundwater flowing through the soils.

2. Methods and materials

2.1. Site description

The study area consists of monitoring sites located in the riparian zone of Walnut Creek, a third-order stream draining a 5218 ha watershed in Jasper County, Iowa (Fig. 1). The area is in a humid, continental region with average annual precipitation of around 750 mm. Walnut Creek watershed is located in the Southern Iowa Drift Plain landscape region of Iowa, an area characterized by steeply rolling hills and a well-developed drainage network (Prior, 1991). Most of the soils are silty clay loams, silt loams or clay loams formed in loess and pre-Illinoian till. In the floodplain of Walnut Creek, the Holocene-age alluvial

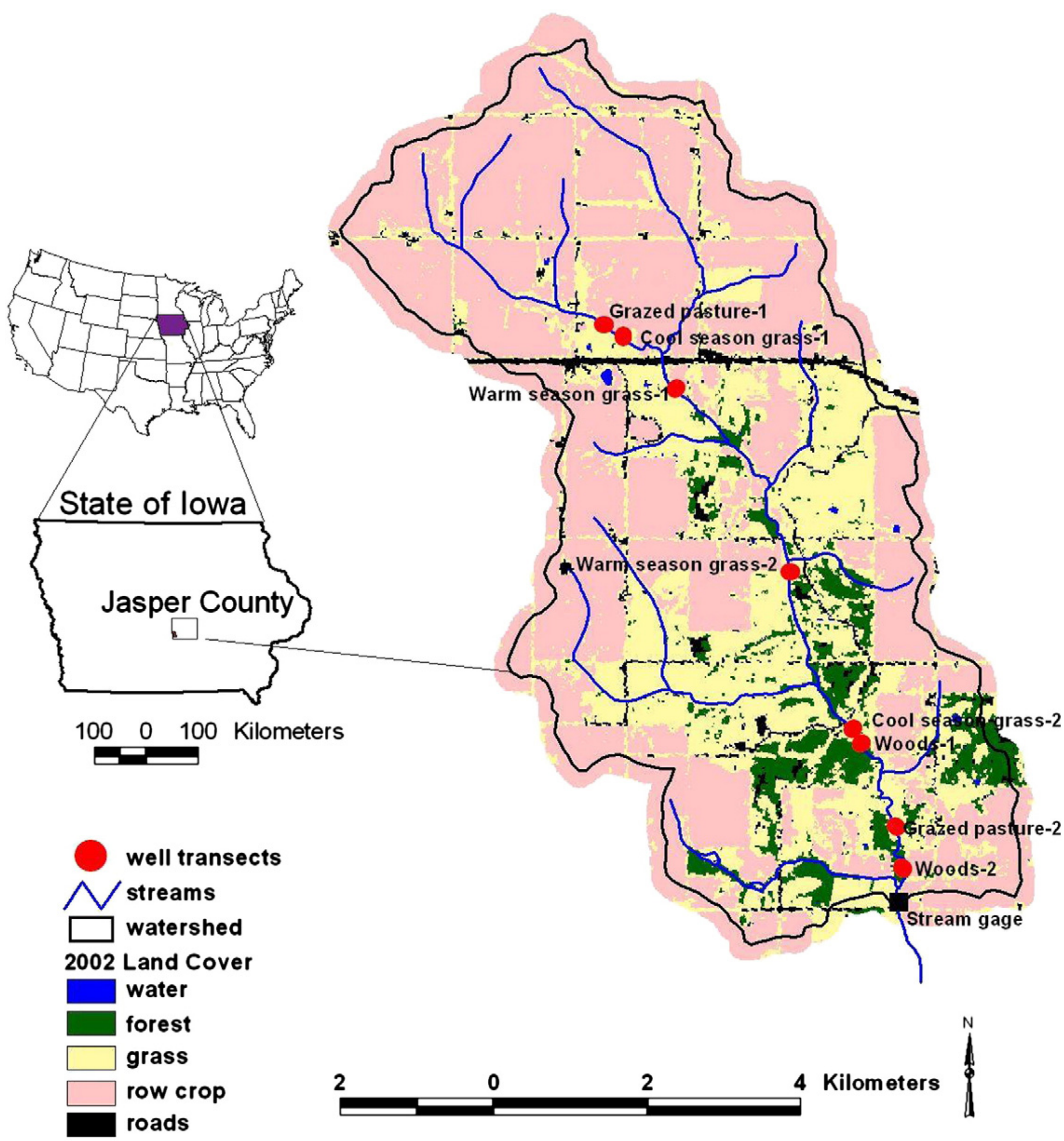

Fig. 1. Location map.

stratigraphy is characteristic of many other valleys across Iowa and in loess-mantled areas of the Midwest (Bettis, 1990; Mandel and Bettis, 1992), consisting of three members of the DeForest Formation (Camp Creek, Roberts Creek, Gunder members; Fig. 3). The three alluvial units were each deposited during a restricted time range during the Holocene, with the Gunder Member deposited between about 10,500 and about 4500 radiocarbon-years B.P., the Roberts Creek Member from 3500 to about 500 B.P. and the Camp Creek Member from about 400 B.P. to the present (Bettis et al., 1992). While texture of each member varies as source materials change, the fills are dominantly silt loam (60–80% silt; Schilling et al., 2009), and buried organic matter is often preserved. The alluvial deposits are nutrient rich, with sediment concentrations of nitrogen and phosphorus averaging 0.11% and 1.3%, respectively, and phosphorus concentrations averaging 574 mg/kg (Schilling et al., 2009). Nutrient concentrations were observed to decrease with depth, with highest values associated with the Camp Creek Member (Schilling et al., 2009).

Walnut Creek is incised to a depth of approximately 3 m into the floodplain, with width–depth ratios generally ranging between 3 and 4 (Schilling and Wolter, 2000). The channel incision cuts through approximately 1 m of the Camp Creek Member and 1.5 m of the Roberts Creek Member and Walnut Creek flows through Gunder Member alluvium. Overall stream sinuosity is approximately 1.2 and many reaches of Walnut Creek have been channelized. The riparian zone of Walnut Creek contains four major perennial land cover types and two replicates of each type were targeted for investigation in this study (total of eight sites; Fig. 1). Dominant vegetation at the two cool season grass sites consisted of *Phalaris arundinacea* L. (reed canary grass), an invasive forage grass adapted to wide extremes in soil moisture but common to wet riparian and wetland areas (Galatowitsch et al., 1999). The two forest sites were located in dense stands of mature riparian forest consisting of a mixture of elm (*Ulmus americana* L.), silver maple (*Acer saccharinum* L.), honey locust (*Gleditsia triacanthos* L.), and green ash (*Fraxinus pennsylvanica* Marsh). These species are fast-growing trees commonly found along disturbed riparian corridors. The two pasture sites consisted of cool season grasses, primarily Kentucky bluegrass (*Poa pratensis* L.). The pastures are continuously grazed from about the beginning of May to the end of October, typical for Iowa (Zaimes et al., 2004). The warm season grass sites were planted by the Neal Smith National Wildlife Refuge (NSNWR) and consist mainly of big bluestem (*Andropogon gerardii* Vitman), little bluestem (*Schizachyrium scoparium* (Michx.) Nash), and Indian grass (*Sorghastrum nutans* (L.) Nash), with up to 15 different native forbs. The northern warm grass site was planted in 2002 whereas the southern warm grass site was planted in 1997. Both sites were previously utilized for row crop production of corn (*Zea mays* L.) and soybeans (*Glycine max* L.) prior to prairie reconstruction by the refuge.

2.2. Field and analytical methods

At each of the eight monitoring well transects, wells were located approximately 1 m (well #1), 20 m (#2), and 40 m (#3) along a line perpendicular to the channel edge (Fig. 2). Soil borings were completed using a 152 mm hand auger and lithologic descriptions were developed from the auger cuttings. Near stream soil borings were approximately 3.6 m deep, whereas the 20 m and 40 m borings were 3.0 m and 2.4 m deep, respectively. The boring depths were greater near the stream and shallower in the floodplain because previous monitoring of water levels in the riparian zone indicated that the water table near the incised stream was deeper near the stream and shallower in distal floodplain areas (Schilling et al., 2004). A factory-slotted PVC well screen (1.5 m long) and PVC riser were installed in the boreholes. A silica sand filter pack was poured around the screen, bentonite chips were added to provide a seal and drill cuttings were backfilled in the rest of the borehole. Ground surface and top-of-casing elevations at the well locations were surveyed to the nearest 0.25-mm and referenced to a

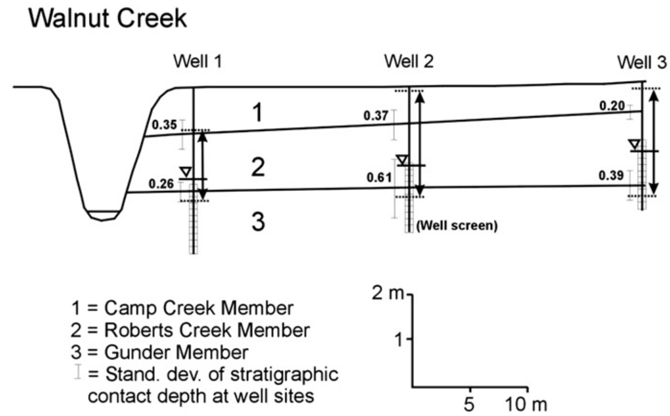

Fig. 2. Generalized cross-section at riparian well monitoring sites. Geologic units are Holocene-age alluvial fills dominated by silt texture (60–80% silt; Schilling et al., 2009). Arrows denote range in high and low water table depths. Variation in depth to stratigraphic contacts is given by standard deviation (in m) and indicates consistent geology among monitoring sites.

local benchmark. A global positioning system (GPS) unit was used to establish horizontal control to the nearest 0.3 m.

Monitoring wells were sampled six times across the growing season from April to November 2009. Water levels in the wells were monitored to 2 mm accuracy using an electronic water level probe. Water samples from wells were collected using a peristaltic pump and analyzed in the field for temperature, specific conductance (SC), pH, dissolved oxygen (DO) and oxidation-reduction (ORP) potential using a YSI water quality meter. Accuracy of the measurements was ± 0.10 °C for temperature, ± 0.2 pH units for pH, $\pm 0.1\%$ for SC, ± 0.2 mg L^{-1} for DO and ± 20 mv for ORP. Due to equipment difficulties, water samples were not field analyzed in October 2009. Well water was slowly pumped to an enclosed sample cup where groundwater chemistry readings were taken with the mulitprobe to minimize exposure to the atmosphere. Water samples for laboratory analysis were field filtered through a 0.45 micron glass fiber filter, transported on ice and analyzed within 24 h of collection. Ammonia–N and nitrate–N were determined by flow injection analysis (QuickChem 8000, Lachat Instruments) using the phenolate (NH_4–N) and cadmium reduction (NO_3–N) methods and soluble reactive phosphorus (PO_4–P) via the molybdenum blue ascorbic acid method. Dissolved organic carbon was measured via Pt-catalyzed, high temperature oxidation (TOC-V Total Organic Carbon Analyzer, Shimadzu Scientific Instruments, Inc., for total non-purgeable organic content from acidified water samples) and dissolved total nitrogen using chemiluminescent detection of nitrogen monoxide.

Differences among well locations relative to Walnut Creek (well 1, 2 and 3 positions) and land cover types (cool season, warm season, woods and pasture) were tested with a Kruskal–Wallis non-parametric one-way analysis of variance on ranks with a 0.05 significance level (Minitab Release 13). All pair-wise comparisons were made using the Mann–Whitney method.

3. Results

3.1. Hydrology

Precipitation varied in 2009, with some daily precipitation events exceeding 40 mm in April, October and November (Fig. 3), and monthly precipitation totals ranging from 130 to 165 mm in April, June, August and October, and 54 to 81 mm during the months of May, July and September. Average water table depths in riparian wells reflected variable precipitation and growing season evapotranspiration. Water tables were higher during spring, lower in the summer and high again in the fall after plant senescence and substantial October rainfall (Fig. 3).

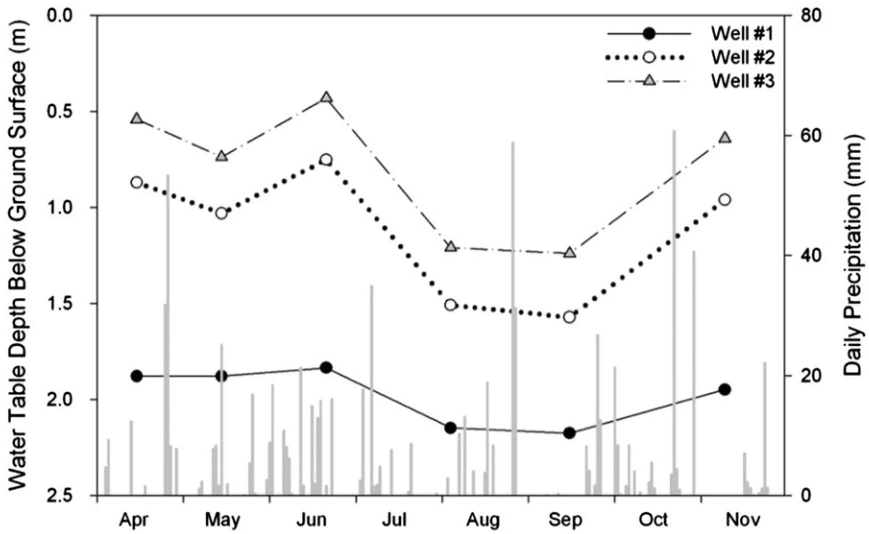

Fig. 3. Mean water table depths in riparian wells and daily precipitation measured during the project.

Water table depth varied significantly with respect to well placement near incised Walnut Creek. Wells located near the incised channel (well #1) had significantly deeper water tables than wells located at 20 m (well #2), which in turn had significantly deeper water tables than those measured at 40 m (well #3) ($p < 0.05$; Fig. 4). Mean water table depths at the #1, #2 and #3 wells were 1.98 ± 0.26 m, 1.12 ± 0.49 m and 0.81 ± 0.51 m, respectively. Among all sites, the water table fluctuated more in the #2 and #3 well positions (variance of 0.25 and 0.26, respectively) compared to the #1 well closest to the stream (variance of 0.07). The water table adjacent to an incised stream is controlled by stream stage and does not fluctuate as much relative to water tables located further in the floodplain riparian zone (Schilling et al., 2004).

Relative to land cover type, water table depths were significantly deeper under the pasture land cover compared to the warm season grass and wood sites ($p < 0.05$; Fig. 5), but there were no significant differences in water table depths between pasture and cool season grass sites, and between cool season grass and either warm season grass or wood sites. Mean water table depths averaged 1.63 ± 0.5 m under pasture, 1.27 ± 0.69 under cool season grass, 1.11 ± 0.57 under warm season grass and 1.09 ± 0.72 under woods.

3.2. Groundwater geochemistry

Among all sites, riparian groundwater had a near-neutral pH and low DO and ORP that averaged 1.48 ± 0.84 mg/l and 1.6 ± 77 mv, respectively (Table 1). Average ammonium concentrations exceeded average nitrate concentrations in the riparian groundwater, averaging 0.46 ± 1.02 mg/l and 0.28 ± 0.81 mg/l, respectively. Maximum concentrations of N-species were similar, with maximum nitrate concentration of 4.94 mg/l measured in a 20-m well (#2 well) at the pasture 1 site, and the maximum ammonium concentration of 6.23 mg/l observed in the 40-m well (#3 well) at the cool season grass 2 site. Phosphorus concentrations averaged 0.18 ± 0.16 mg/l among all sites and peaked at a concentration of 0.78 mg/l at the cool season grass 2 site (well #2). DOC concentrations showed wide variation in riparian groundwater, ranging from 0.8 to 46.5 mg/l among all sites, averaging 5.85 mg/l.

3.2.1. Influence of well location relative to stream

Variations in groundwater geochemistry were evident among the monitoring wells depending on well location. Temperature, pH and specific conductance did not show significant differences among riparian

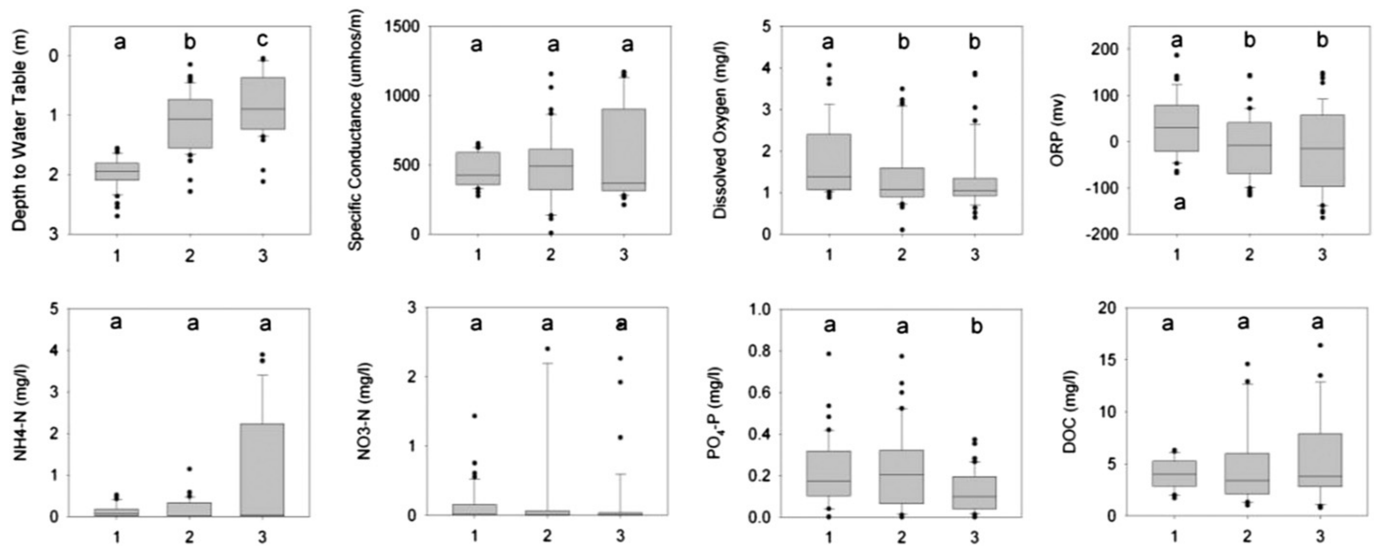

Fig. 4. Classification of water quality variables by wells located approximately 1 m (#1), 20 m (#2), and 40 m (#3) from the channel edge. Letters denote significant differences among the units at $p < 0.05$. The box lots illustrate the 25th, 50th, and 75th percentiles; the whiskers indicate the 10th and 90th percentiles; and the points represent data outliers.

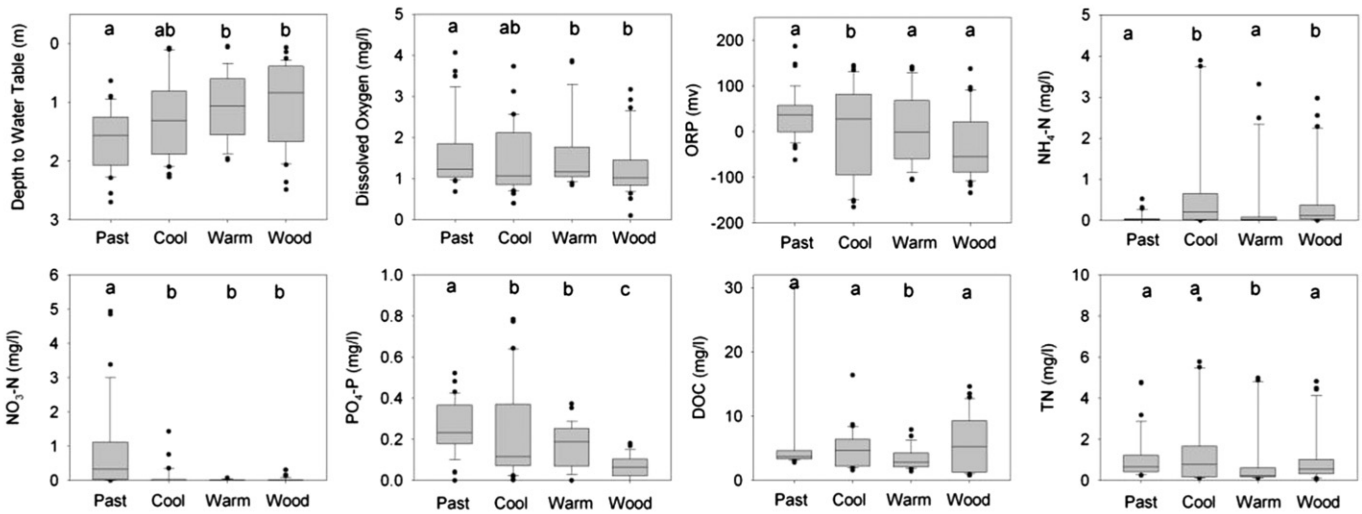

Fig. 5. Classification of water quality variables by land cover type. Box plot notation is the same as Fig. 4.

well placement, but variations in dissolved oxygen and ORP were statistically significant ($p < 0.05$). Dissolved oxygen concentrations and ORP were significantly higher in groundwater sampled from the 1-m well (well #1) compared to groundwater measured in wells #2 and #3 (Fig. 4). Mean DO concentrations were 1.74 mg/l in well #1 and 1.36 mg/l and 1.32 mg/l in wells #2 and #3, respectively, whereas median ORP values were similarly higher in the #1 wells (32 mv) than in the #2 wells (−10 mv) and #3 wells (−14 mv). No significant differences were observed in ammonium or nitrate concentration based on well locations 1 m, 20 m or 40 m from the stream channel ($p > 0.05$). However, higher maximum ammonium values and greater variance in ammonium concentrations were observed in the #3 wells (Fig. 4). PO_4–P concentrations were significantly lower in the #3 wells compared to the #1 and #2 wells (Fig. 4).

3.2.2. Influence of land cover

Significant differences were observed in DO and ORP values between pasture and wood sites (Fig. 5). DO concentrations were significantly higher ($p < 0.05$) in pasture riparian wells (1.64 mg/l) compared to riparian woods (1.27 mg/l), and ORP was significantly higher ($p < 0.05$) in the pasture (35 mv) than in the woods (−34 mv). No differences were observed in DO and ORP with respect to riparian groundwater under cool season or warm season grass (Fig. 5), nor were significant differences observed in temperature, pH or specific conductance based on land cover type.

Ammonium concentrations were significantly higher in riparian groundwater under cool season grass and woods compared to pasture and warm season grass, whereas nitrate concentrations were significantly higher under the pasture land cover than the other land cover types (Fig. 5). Significant differences were also observed in phosphorus concentrations with respect to land cover type (Fig. 5). PO_4–P concentrations were significantly higher under pasture and lower under the woods, although they were not significantly different between cool and warm season grass sites. DOC concentrations were significantly lower under warm season grass and not statistically different among the other land cover types.

3.3. Relation of water table depth to water quality

Among all samples, water quality parameters were related to water table depth regardless of well location or land cover type (Fig. 6). This analysis includes factors other than channel incision or land cover type which might influence water table depth and groundwater quality, including seasonal water table fluctuations (Fig. 3) or variations in landscape geomorphology. Among geochemical parameters, temperature was positively related to water table depth, whereas specific conductance and ORP of riparian groundwater were negatively related ($p < 0.05$). Dissolved oxygen was only weakly positively related ($p < 0.1$). Among nutrients, ammonium and total nitrogen were significantly positively related to water table depth, but PO_4–P concentrations were significantly negatively related ($p < 0.05$; Fig. 6). Nitrate and DOC were not significantly related to water table depth in the Walnut Creek riparian groundwater.

4. Discussion

4.1. Riparian groundwater quality compared to regional criteria

Study results indicate that riparian groundwater under perennial cover near incised Walnut Creek contains concentrations of nutrients N, P and C considerably lower than typically reported beneath annual cropping systems. For example, groundwater nitrate concentrations under cropped systems often exceed 10 mg/l (Schilling and Wolter, 2001; Spalding and Exner, 1993), whereas nitrate concentrations under the perennial cover at Walnut Creek were very low averaging less than 0.3 mg/l. Ammonium concentrations typically exceeded nitrate concentrations, but average ammonium concentrations remained less than 0.5 mg/l. Both nitrate and ammonium concentrations peaked at concentrations that may represent an environmental concern

Table 1
Summary of water quality characteristics for all wells sampled in this study.

	Depth to water table (m)	Temp (°C)	pH	Sp cond (uS/m)	DO (mg/l)	ORP (mv)	NH_4–N (mg/l)	NO_3–N (mg/l)	PO_4–P (mg/l)	DOC (mg/l)	TN (mg/l)
n	130	130	128	130	130	130	129	129	129	129	129
Mean	1.28	13.04	6.54	515	1.48	1.6	0.45	0.28	0.18	5.85	1.17
St. dev.	0.66	3.00	0.47	263	0.84	77	1.01	0.80	0.16	6.90	1.58
Median	1.33	13.23	6.53	468	1.10	5	0.03	0.01	0.15	3.80	0.55
Min.	0.05	6.65	5.45	7	0.10	−165	0.00	0.00	0.00	0.80	0.05
Max.	2.70	19.38	7.95	1168	4.06	187	6.23	4.94	0.78	46.50	8.81

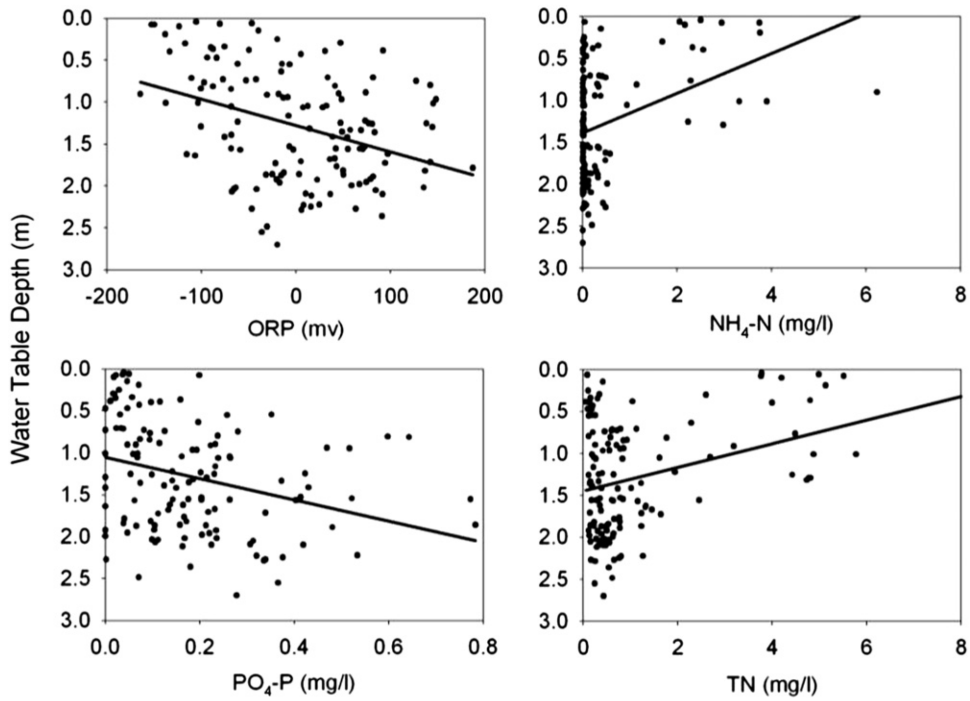

Fig. 6. Relation of water table depth to riparian groundwater quality among all sites and sample dates. All relationships shown were significant at $p < 0.05$.

(4.9 and 6.2 mg/l, respectively). Regional total nitrogen criteria for streams in Ecoregions 47 and 40 have been set at 2.62 and 0.86 mg/l, respectively (USEPA, 2000). The combined nitrate and ammonium concentrations measured in the riparian groundwater beneath perennial buffers (~0.8 mg/l) approach the total nitrogen criteria for the region.

Average PO_4–P concentrations (0.2 mg/l) were similar to average concentrations reported by Schilling and Jacobson (2008) for typical Holocene strata (0.1–0.3 mg/l), although maximum values reported herein (0.8 mg/l) were not as high as those previously reported (1.3 mg/l). Phosphorus concentrations were higher than those reported for other aquifers and aquitards in Iowa (Burkart et al., 2004), and may be considered high relative to proposed nutrient criteria for streams (0.18 and 0.092 mg/l for Ecoregions 47 and 40, respectively; USEPA, 2000).

We should note that the adjacent land cover upslope of the riparian zones assessed in this study largely consisted to perennial cover that would be expected to contribute low concentrations of nitrogen or phosphorus to the riparian groundwater. Upland groundwater in a reconstructed prairie chronosequence at NSNWR had mean concentrations (n ~ 107) of nitrate, ammonium, and phosphorus of 5.4, 0.08 and 0.06 mg/l, respectively (Schilling and Jacobson, 2010). In this study, we focused on assessing the effects of lithology and channel incision on groundwater quality within the buffer zone in-situ, not measuring the effects of a riparian buffer to reduce nitrate delivery from adjacent cropped fields, which has been well documented in the literature (e.g., Dosskey, 2001; Schultz et al., 1995). Study results indicate that groundwater nitrogen (nitrate and ammonium) and phosphorus concentrations in riparian zones under perennial cover, unaffected by upslope contributions, approach or exceed regional nutrient criteria.

4.2. Effects of channel incision and land cover type

Results from this study are consistent with research showing deeper water tables and aerobic conditions developing in the near-stream riparian zones of incised channels (Groffman et al., 2002; Schilling and Jacobson, 2008). Deeper water tables and aerobic soil conditions are thought to result in conditions conducive for mineralization of soil N. In this study, while deeper water tables near incised Walnut Creek resulted in significantly higher DO and ORP levels in groundwater located 1-m from the channel edge, higher DO and ORP did not result in higher groundwater nitrate concentrations in the near-stream riparian zone. In fact, no significant differences were observed in ammonium or nitrate concentration based on well locations 1 m, 20 m or 40 m from the stream channel, despite high concentrations of soil N (average of 0.11%; Schilling et al., 2009). We believe that the lack of significant N mineralization in the stream riparian zone is due to the perennial vegetation covering the riparian soils. Previous work in the Walnut Creek riparian zone during an ecological restoration (the cool season grass 2 site used in this study) showed that when the perennial cover was removed, riparian soils were capable of generating nitrate concentrations from 20 to 40 mg/l in riparian groundwater (Schilling and Jacobson, 2008; Schilling et al., 2006). The lack of similar nitrate concentrations developing in the riparian zone of the same watershed despite development of more aerobic conditions near the incised channel suggests that perennial vegetation may be the key component needed to reduce N loss near incised streams. Perennial vegetation captures infiltrating water through increased evapotranspiration (compared to seasonal crops) and scavenges excess nitrogen in the vadose zone available for leaching. In the Walnut Creek watershed the four perennial vegetation types evaluated in this study were equally adept at minimizing accumulations of nitrate that may develop in the unsaturated zone of an incised stream.

The rooting depths of perennial vegetation types evaluated in this study were not a significant factor in low groundwater nitrate concentrations, as rooting depths varied from mature trees (1–2 m deep) to cool season grass (pasture and reed canary grass <1 m) based on visual assessments of exposed stream banks. Similar rooting depths beneath trees (>1.8 m) and cool and warm season grass (<1.2 m) were also observed by Tufekcioglu et al. (1999). With the depth to the water table increasing near the incised channel, roots of most perennial vegetation types in the riparian zone were above the water table at the 1-m well location. However, rooting depths may be less critical in the fine-grained aquifer materials assessed in this study as the capillary fringe can extend upward 1–2 m in silt (Gillham, 1984).

In some riparian areas, comparisons of groundwater concentrations to well placement and land cover were confounded by other landscape patterns (Johnson et al., 2003; Malard et al., 2002). Despite similar geologic conditions and stratigraphy at the study sites (Fig. 2), it was evident during the study that water table depths were affected, in part, by the location of the well transects with respect to the sinuosity of the Walnut Creek stream channel. For example, in locations where Walnut Creek has been straightened, local groundwater flow was directed perpendicular toward the stream channel (parallel to the well transect orientation) (Fig. 7). In other areas, Walnut Creek is very sinuous and the orientation of the well transect, while perpendicular to the stream channel in one direction, was parallel to the channel in another direction. In this case, hydraulic gradients directed groundwater flow radially to the stream which drained the riparian zone from multiple directions. Riparian water table depths were deeper in areas where the stream channel was sinuous, and sinuosity was generally highest in the pasture sites. Hence, it was difficult to discern whether the relation of N and P to water table depths in pasture areas was a function of riparian well location relative to the stream, land cover, channel sinuosity, or a combination thereof. Pasture sites had the lowest water table and higher DO and ORP compared to other land covers (Fig. 5). Grazing management is yet another factor potentially contributing to higher NO_3–N concentrations beneath pastures as increased N mineralization has been observed in grazed systems (Frank and Groffman, 1998; Johnson and Matchett, 2001). At the two pasture sites evaluated in our study, the upstream pasture 1 site was more heavily grazed than the downstream pasture 2 site and had higher mean NO_3–N concentrations (1.6 compared to 0.3 mg/l). Thus, while NO_3–N concentrations were significantly higher under the pasture land cover, we are not able to determine whether the concentrations are associated with lower water tables in a sinuous riparian zone, or increased N-losses from intensive grazing and manure derived from pastured cattle. Additional study of the pasture areas, including installation of multiple well transects in sinuous channel areas, is needed to resolve this issue more conclusively.

We hypothesize that higher phosphorus concentrations in pastured riparian zones are due to P inputs from cattle manure. Previous work on the sedimentology of riparian soils in Walnut Creek did not show significant differences in sediment total P concentrations by land cover (Schilling et al., 2009). Average PO_4–P concentrations in riparian groundwater under grazed pasture (0.26 mg/l) were nearly double the average PO_4–P concentrations of the other land cover types (0.16 mg/l). Because of this land use factor, and lower water tables under sinuous pastured sites, phosphorus concentrations were negatively related to water table depth (Fig. 6). This negative relation is counter to established conditions of higher P concentrations found in groundwater. Phosphorus is mobilized when Fe-bound P is released from soils under anaerobic conditions that develop under high-water table conditions (Tomer et al., 2010). Carlyle and Hill (2001) suggested that organic P mineralization may also influence P concentrations in organic-rich riparian zones. In this study, no significant relation was observed in PO_4–P concentrations and DOC ($p = 0.29$). Overall, study results suggest that relations of groundwater PO_4–P concentrations to riparian conditions may be complicated by many factors in a single watershed that make straightforward cause–effect relationships difficult to establish.

It was initially surprising to observe that warm season grass sites had the lowest DOC concentrations in riparian groundwater because subsurface carbon stocks are typically higher under prairie conditions (Fornara and Tilman, 2008). However, in Walnut Creek watershed, subsurface conditions under the two warm season sites may be more closely linked to the historical vegetation patterns (row crop agriculture) rather than their current vegetation type. Both warm season sites were only recently planted in warm season grasses (1997 and 2002 plantings), so their soil nutrient profiles are likely influenced by the decades of agricultural production that preceded the prairie reconstruction. Low TN concentrations at the former cropped, warm season grass sites may also be associated with long-term agricultural production that depleted soil N levels. In contrast, historical air photographs suggest that the pasture, cool season and riparian forest sites have remained relatively unchanged since the 1940s. Marquez et al. (2004) also observed that soil aggregate stability was similar between a 7-year old switchgrass plot and cropped systems due to the young age of the experimental restoration. Thus, it may be that differences in the groundwater DOC and TN concentrations under various vegetation types reflect more accurately differences in long-term vegetation type on soil nutrient stocks rather than short-term vegetation changes. In addition to vegetation type, differences in historical land management practices may also affect nutrient comparisons across land cover types.

4.3. Regional significance

Nutrient concentrations measured in the riparian zone of Walnut Creek are representative of the region. The riparian zone of Walnut Creek in southern Iowa is typical of second to fourth-order streams in the loess-mantled glaciated Midwest, inasmuch as 1) the subsurface geology consists of organic-rich, silty alluvium deposited during the Holocene (Baker et al., 1992; Schilling et al., 2009); 2) the stream channel is incised into the floodplain; and 3) perennial riparian vegetation of grasses, woods and pasture dominate the riparian corridor. Hence, results from our study suggest that for similar settings in the glaciated Midwest, nutrient concentrations in riparian groundwater under

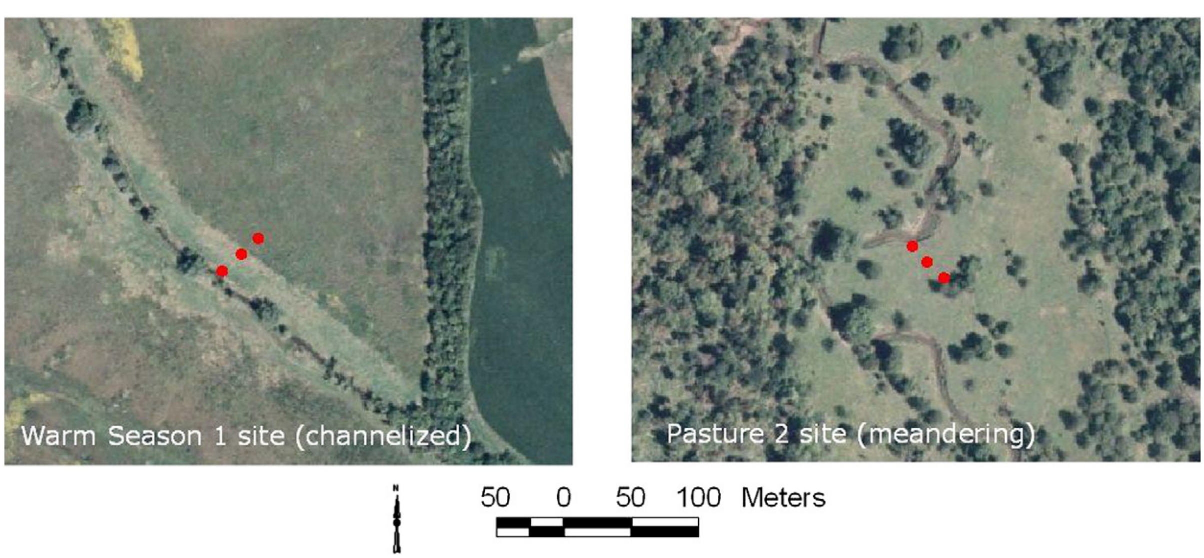

Fig. 7. Location of well transects in straightened and meandered segments of Walnut Creek.

similar perennial cover conditions would be expected to average approximately 0.3 mg/l NO_3–N, 0.5 mg/l NH_4–N, 0.2 mg/l PO_4–P and 6 mg/l DOC.

Previous work reporting on riparian soil characteristics in Walnut Creek watershed suggested that subsurface sediments contain nutrient concentrations that may adversely impact water resources (Schilling et al., 2009). The National Agricultural Statistics Service Crop Data Layer (CDL) for the Major Land Resource Area (MLRA) 108 and 109 regions (Fig. 8) provides an estimate of the amount of riparian land area under agricultural or perennial cover in the Iowa portion of MLRA 108 and 109 regions. Of the 24,055 km of streams, 61.5% of the stream network had riparian land cover consisting of agricultural land, and 30.5% of the riparian land cover consisted of non-agricultural perennial cover. Our results apply to the 30.5% of the perennially-buffered streams in the region.

Assuming average nutrient concentrations in riparian groundwater and the extent of perennially-buffered streams, we can estimate the nutrient loads delivered to streams in the region to assess potential impacts. We used Darcy's Law to estimate the water yield from the perennial riparian vegetation:

$$Q = KiA$$

where Q is the groundwater discharge volume (in m^3/year), K is the hydraulic conductivity of the Holocene alluvium based on the mean saturated K (Ksat) of riparian soils (ranging from 1 to 4×10^{-5} cm/s), i is the hydraulic gradient across the riparian zone (0.02), and A is the cross-sectional area of groundwater discharge into the channel assuming discharge from the stream channel length and a saturated thickness of 2 m. Results suggest that 6.41×10^8 m^3 of groundwater flows through Holocene alluvium in MLRA 108 and 109 regions every year, of which 1.95×10^8 m^3 of groundwater flows through perennial riparian buffers. Assuming average nutrient concentrations (see above paragraph), we estimate that 65 metric tons (Mg) of NO_3–N, 108 Mg of NH_4–N, 43 Mg of PO_4–P and 1291 Mg of DOC are discharged each year from riparian zones that are buffered with perennial vegetation. We compared the total inorganic nitrogen export and phosphorus export to loading estimates from MLRA 108 and 109 regions recently developed for the Iowa Nutrient Reduction Strategy (INRS, 2013). Results suggest that N and P discharge through perennial buffers contributes approximately 0.3% and 0.7% to the total regional N and P export to streams in MLRA 108 and 109 regions. Based on this loading analysis, nutrient export from groundwater flowing through perennial buffers along incised streams in the region does not appear to adversely impact water resources. This is mainly due to limited groundwater volumes discharging from the fine-grained alluvial sediments since nutrient concentrations present in riparian groundwater may be a concern, particularly for phosphorus.

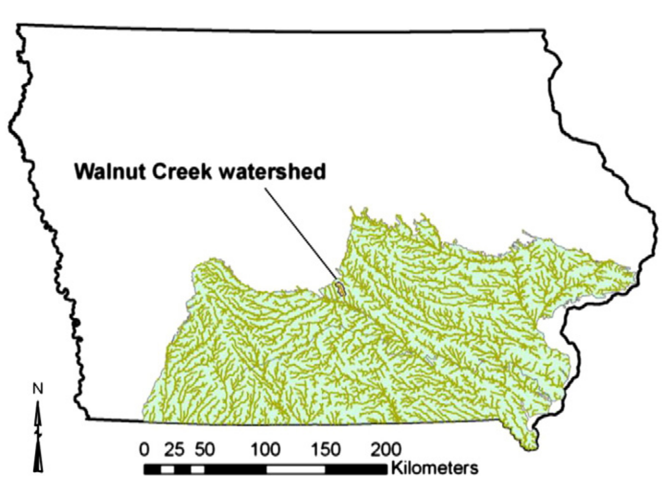

Fig. 8. Extent of perennial streams in MLRA 108 and 109 regions.

5. Conclusions

Groundwater samples collected from riparian wells installed 1 m, 20 m and 40 m from an incised channel under four replicated land covers were used to assess the effectiveness of natural riparian buffers to reduce nutrient losses to incised streams in southern Iowa. Results showed that channel incision greatly affects water table depths in the stream riparian zone by lowing water tables in the near-stream zone and creating a region of elevated DO and ORP conditions within 1 m of the channel compared to conditions 20 m and 40 m from the channel edge. Contrary to expectations, more aerobic conditions near the channel did not result in higher nitrate concentrations in groundwater, as perennial cover at all the land cover sites was evidently sufficient to keep nitrate accumulation and leaching to a minimum. Phosphorus concentrations appeared to be more sensitive to land cover type than either nitrogen or carbon, with highest concentrations under grazed pasture and lowest concentrations under riparian woods.

Perennial vegetation along many incised, perennial streams and rivers in southern Iowa and northern Missouri is assumed to provide natural riparian buffers against subsurface nutrient losses from shallow groundwater. Knight et al. (2011) reported that natural remnant forests in the Midwest provide substantial buffering capacity against concentrated flow paths and sediment losses. Our study results indicate that perennial buffer systems offer additional protection against nutrient losses from groundwater discharging into incised streams from nutrient-rich Holocene alluvium, particularly with respect to nitrate. Subsurface nutrient loads delivered through perennial buffers do not appear to be a significant source to regional streams, however average PO_4–P concentrations (0.2 mg/l) in riparian groundwater were elevated compared to regional nutrient standards for streams, suggesting that even riparian groundwater under perennial cover may have difficulty in meeting the criteria when delivered to streams as baseflow.

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