2012

Concentrated Flow Paths in Riparian Buffer Zones of Southern Illinois

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Agroforest Syst (2012) 84:191–205
DOI 10.1007/s10457-011-9457-5

Concentrated flow paths in riparian buffer zones of southern Illinois

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Received: 15 March 2011 / Accepted: 1 November 2011 / Published online: 8 December 2011

Abstract Riparian buffers in agricultural landscapes should be designed to trap pollutants in overland flow by slowing, filtering, and infiltrating surface runoff entering the buffer via sheet flow. However, observational evidence suggests that concentrated flow is prevalent from agricultural fields. Over time sediment can accumulate in riparian buffers forming berms that restrict sheet flow; these berms ultimately back up surface runoff, resulting in an eventual breakthrough that concentrates overland flow. This study examines the occurrence of concentrated flow paths (CFPs) in riparian buffers at both the field and watershed scale. At the field scale, intensive topographic surveys were conducted at ten field sites in southern Illinois. To assess the prevalence of CFPs at the watershed scale, three watersheds in southern Illinois were selected for walking stream surveys along randomly selected 1,000 m reaches. CFPs were identified in all topographic surveys and all walking stream surveys. Among field sites, concentrated flow accounted for 82.5–100% of the drainage leaving the agricultural fields. Sediment berm accumulation was identified at all field sites and was positively correlated with CFP size. At the watershed scale, CFPs were more abundant in agricultural areas compared to forested land. Results from this study indicate that concentrated flow was prevalent across all study sites at both the field and watershed scale. Thus, surface water quality may suffer in areas with poorly functioning buffers, and managers must consider the occurrence of CFPs when designing and maintaining riparian buffers to protect stream water quality.

Keywords Concentrated flow · Nonpoint source pollution · Riparian forest buffer · Sediment berm · Sedimentation · Sheet flow

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Introduction

The sediment filtering capabilities of riparian buffers have been noted for over three decades (Young and Onstad 1976; Lowrance et al. 1984, 1986; Cooper et al. 1987; Dillaha et al. 1989; Osborne and Kovacic 1993; Daniels and Gilliam 1996; Schmitt et al. 1999; Dosskey 2001; Lee et al. 2003; Schultz et al. 2004; Schoonover et al. 2006), establishing a large body of literature advocating the use of these valuable conservation practices. Sediment reduction from agricultural surface runoff has been attributed to plant roots, which hold soil in place and increase infiltration, and the above-ground plant parts, which reduce runoff velocity by increasing surface roughness (Robinson et al. 1996; Schmitt et al. 1999; Dosskey 2001).

Sediment trapping efficiencies of vegetated riparian buffers have been consistently reported at high levels in studies of both buffer width and buffer vegetation. Riparian buffers at widths ranging from 3 to 21 m have been examined in work of Dillaha et al. (1989), Robinson et al. (1996), Lee et al. (1998, 2000, 2003), Schmitt et al. (1999), and Schoonover et al. (2006). These studies suggest that sediment filtering capacities above 70% were typically achieved at widths of as small as 4.3–8.5 m. Several have concluded that multi-species buffers, consisting of a mixture of grass and trees, provide superior sediment filtering capacities to those of a single species (Lee et al. 2000, 2003; Lyons et al. 2000), while Schmitt et al. (1999) found no impact on sediment reduction from multi-species buffer compositions. Schoonover et al. (2006) identified giant cane (*Arundinaria gigantea* (Walt.) Muhl.), as superior sediment filtering buffer vegetation compared to forested buffers. Although research has identified riparian buffers as sediment-reducing conservation practices, little attention has been given to the performance or maintenance of these buffers over time.

For optimal performance of riparian buffer functions, overland flow must enter buffers uniformly as dispersed sheet flow across the buffer area (Dillaha et al. 1989; Myers et al. 1995; Robinson et al. 1996; Lyons et al. 2000; Dosskey et al. 2002; Schultz et al. 2004; Knight et al. 2010). Therefore, concentrated flow must be minimized for continued filtering effectiveness of riparian buffers over the long term (Dillaha et al. 1989; Dosskey et al. 2002; Schultz et al. 2009). To date, little research has focused on the issue of concentrated flow through riparian buffers. Knight et al. (2010) documented CFPs in remnant forest buffers, observing that buffers without accompanying grass filters were breached by CFPs that likely formed from flow concentration along the buffer edge focusing the runoff into CFPs. Qualitative field observations by Dillaha et al. (1989) noted that surface runoff frequently became concentrated, only flowing through portions of vegetative filter strips in the Chesapeake Bay and Chowan River basins of Virginia. Sediment accumulation was observed to reduce buffer function over time on plots with simulated rainfall (Dillaha et al. 1989). They also noted that sediment from surface runoff was primarily deposited in filter strips at or near the agricultural field edge. Dosskey et al. (2002) noted similar results and identified sediment accumulation and the development of low berms at the field edge as a reason for reduced buffer function in southeastern Nebraska. Berms such as these have been noted by Hayes et al. (1979) to form upslope of the riparian buffers at the field margin. This accumulation of berm-forming sediments is likely a result of sediment settling at the field edge due to higher water infiltration rates within the buffer vegetation (Dillaha et al. 1988) and reduced surface runoff velocity (Schultz et al. 2009).

Dosskey et al. (2002) observed that the process of berm formation tends to promote concentrated flow paths (CFPs) through riparian buffers. In their research they developed a method of assessing CFPs from visual assessments and modeling (Dosskey et al. 2002). Conclusions from their study report significant reduction in sediment attenuation from concentrated flow as determined by VFSMOD modeling procedures. However, field data collection to identify areas of flow concentration was conducted with a combination of visual interpretation and elevation measurements. More recently, Knight et al. (2010) studied the resistance to CFPs in riparian forest buffers constructed with grass filters at the field edge compared to forested buffers with no associated filter. They reported significantly more active CFP development in buffers with no grass filter present. However, much of the CFP volume reported in their study was focused on flow paths within the agricultural field itself. To date, these two papers by Dosskey et al. and Knight et al. are the most extensive look at CFPs in riparian buffers. Research that accurately quantifies CFP size, location and contributing drainage areas would greatly complement the work of Dosskey et al. (2002) and Knight et al. (2010) by further characterizing the occurrence of CFPs in agricultural areas.

This study is built around our conceptual model of sediment berm accumulation within riparian buffers (Fig. 1). During a rain event in a typical agricultural field, where the general slope of the field is toward the buffer and stream, surface runoff is generated when the infiltration capacities of the soil are exceeded (Horton 1933). As rainfall persists, surface runoff energy increases and leads to soil detachment and

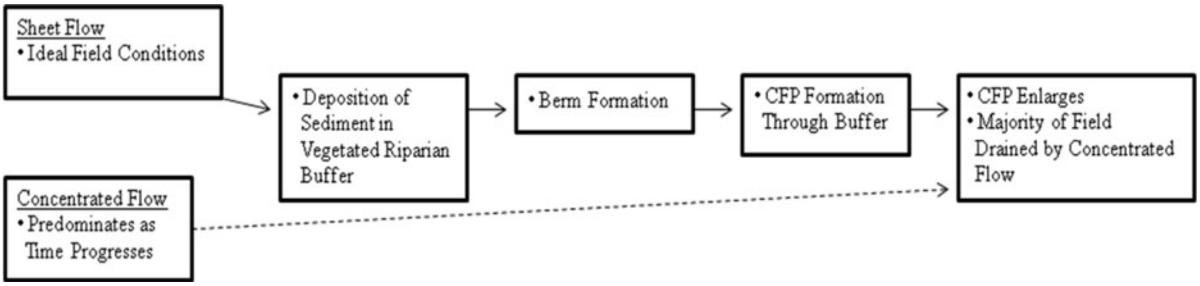

Fig. 1 A conceptual model of sediment accumulation within riparian buffers. According to this model, accumulating sediment concentrates runoff along the buffer edge resulting in the development of a CFP

entrainment. The entrained sediment then gets carried toward the down-slope buffer.

As surface runoff reaches the buffer edge, velocity can be slowed by increased surface roughness and higher infiltration within the buffers. Under ideal conditions, such as in a newly installed or restored buffer, surface runoff would contact the buffer edge as evenly dispersed sheet flow. Sheet flow would allow entrained sediment to settle out in the buffer as runoff velocity was reduced by vegetation. Over repeated storm events, the continual inputs of sediment can result in the development of a sediment berm that eventually restricts sheet flow, and leads to runoff concentration along the berm.

Post berm formation, impounded surface runoff will breach the sediment berm at the lowest elevation along it and create an area of concentrated runoff through the berm. At this point, CFP has been initiated. During subsequent rainfall, water will continue following the newly developed flow path and potentially lead to the formation of a larger gully due to excessive water volumes passing through the buffer at a single point. As runoff continues, the newly formed CFP will modify its width and depth to accommodate the new flow volume that it receives from the upslope catchment. Over time, CFPs begin to emulate ephemeral drainages, where a distinct channel and catchment area can be identified.

The goals of this research were to examine data collected from 3 watersheds in southern Illinois to analyze the conditions that lead to occurrence of CFPs at the watershed scale, and to accurately quantify CFP size and related field attributes. To achieve these goals, the study was split into a field scale analysis, on ten individual agriculture field sites, and a watershed scale analysis in three major watersheds of the Cache River basin of southern Illinois. Our primary hypothesis was that CFPs through riparian buffers were present and measurable with our survey methods at the field and watershed scale in southern Illinois. Secondly, we hypothesized that sediment berm accumulation occurred within these buffers in tandem with the development of CFPs.

Methods

Study area

All study sites were within the Cache River drainage basin (8 Digit Hydrologic Unit Code 07140108) in southern Illinois (Fig. 2). This area is located at the confluence of four major physiographic provinces: the Coastal Plain, the Interior Low Plateaus, the Ozark Plateaus, and the Central Lowlands (Illinois Department of Natural Resources 1997a). The Cache River basin has received state, federal and international recognition for unique natural communities, such as cypress-tupelo swamps and extensive bottomland forests, which remain intact despite a history of land conversion (Illinois Department of Natural Resources 1997b).

Presettlement land cover within the Cache River watershed was estimated to be nearly 80% forest cover, accompanied by large, dense stands of giant cane (*Arundinaria gigantea* (Walt.) Muhl.) (Illinois Department of Natural Resources 1997b). Widespread logging, land clearing and conversion to agriculture resulted in agricultural and pastural areas accounting for approximately 64% of the watershed in 2000, while forest cover only accounted for approximately 30% (US Department of Agriculture 2000). Giant cane has been reduced to only 2% of its original range (Noss et al. 1995; Platt and Brantley 1997).

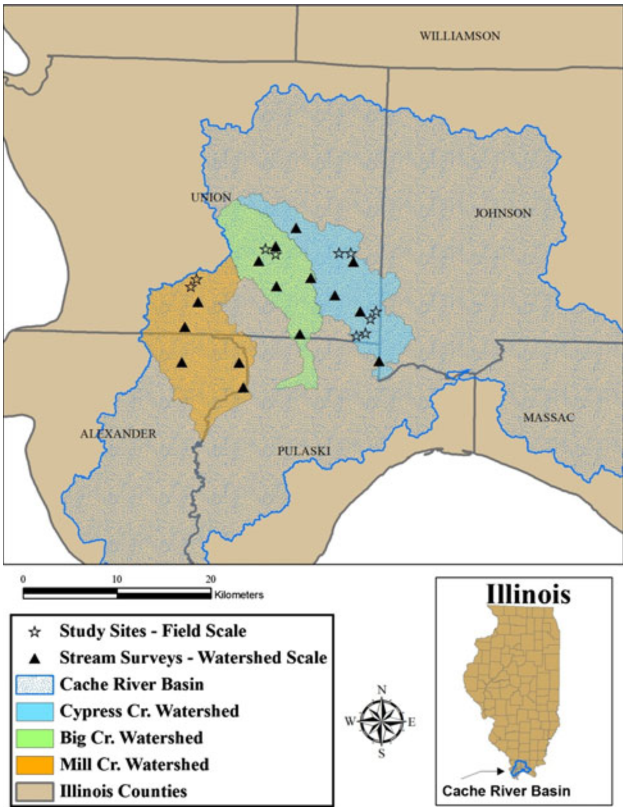

Fig. 2 Locations of study sites and streams surveyed in the Cache River Watershed of southern Illinois

The mean annual temperature for southern Illinois is 13.7°C; average summer temperatures range from 17 to 32 C, and winter temperatures ranging from −5 to 7 C (Illinois Department of Natural Resources 1997a). Mean annual rainfall is 121.5 cm, with the greatest amount of precipitation occurring in the early spring and late fall (Illinois Department of Natural Resources 1997a). The driest periods of a typical year are: midwinter, summer, and early fall. The region exhibits a relatively long growing season, with approximately 230 frost-free days (Illinois Department of Natural Resources 1997b).

Field scale analysis

Site selection and surveys

All field scale study sites lie within three watersheds of the Cache River basin: Big Creek (9,143 ha), Cypress Creek (11,304 ha), and Mill Creek (13,808 ha). Ten agricultural fields containing forested riparian buffers that received overland flow inputs from agricultural fields were selected throughout the watersheds (Table 1). Each study site included an agricultural field and the adjacent riparian buffer. Of these sites, four were on U.S. Fish and Wildlife Service property and six were privately owned. In several cases, adjacent study sites were established within the same larger agricultural field where two watersheds could be easily topographically distinguished. Five of the agricultural fields at the study sites were under a conventional tillage regime and five were in conservation tillage. Conventional tillage regimes usually involve significant tillage applications each year that leaves a large percentage of the soil surface exposed. By contrast, conservation tillage regimes maintain at least 30% residual cover on the soil surface during the non-cropped part of the year (USDA 2000).

None of the agricultural fields were intentionally designed to have riparian buffers. Instead, each site was either a remnant stand of forest that was not cleared for agriculture, or simply a riparian area that was allowed to slowly reforest over time after the initial land clearing. Fields that had constructed drainage structures that altered surface runoff and by-passed riparian buffers (i.e., tile drainage, constructed

Table 1 Site characteristics of the ten field scale study sites within the Cache River Basin of southern Illinois

Site	Watershed	Ownership	Tillage regime	Adjacent stream type	Soil map units Buffer area	Soil map units Agricultural field area
1	Cypress Creek	Public	Conventional	Ephemeral	1334A	1334A, 8787A
2	Cypress Creek	Public	Conservation	Ephemeral	1334A	79C3, 79B, 214B, 214C3, 1334A
3	Mill Creek	Private	Conventional	Intermittent	79D3	79B, 79C2, 79D3
4	Mill Creek	Private	Conventional	Intermittent	79D3	79B, 79C2, 79D3
5	Cypress Creek	Public	Conservation	Ephemeral	8334A, 79C3	79C3, 214B, 214C3
6	Cypress Creek	Public	Conservation	Ephemeral	8334A	214B, 214C3, 3288A
7	Big Creek	Private	Conservation	Perennial	8331A	79C3, 79F, 8331A
8	Big Creek	Private	Conservation	Perennial	8331A	79C3, 79E3, 8331A
9	Cypress Creek	Private	Conventional	Perennial	8333A	214C3, 8334A
10	Cypress Creek	Private	Conventional	Perennial	8333A	214C3, 8334A

drainage channels, grassed waterways, etc.) were excluded from consideration for this study.

On all sites, the primary buffer vegetation was mature forest consisting of an overstory dominated by typical bottomland species of the Midwest, such as sycamore (*Platanus occidentalis*), pin oak (*Quercus palustris*), hackberry (*Celtis occidentalis*), red maple (*Acer rubrum*), green ash (*Fraxinus pennsylvanica*) and boxelder (*Acer negundo*). Herbaceous ground cover near the buffer edge was generally more dense. However, herbaceous vegetation within buffers typically became more sparse near the streamside of the buffer as closed canopy reduced light reaching the ground. Four of the ten riparian buffers contained areas occupied by giant cane. Giant cane is a bamboo-like species native to southern Illinois that typically exists in small, dense stands called canebrakes. At our study sites, the canebrakes ranged from 0.002 to 0.07 ha and only occupied a small percentage of each buffer area (0.2–11.0%).

All sites were surveyed from the April 2007 to March 2008 to collect spatial data using a TOPCON® GTS 233W electronic total station (TOPCON Corp., Tokyo, Japan). Intensive surveys were performed at each site to record the surface topography, averaging 2,679 points per site and 766 points per hectare. Survey points were collected intensively across each site to measure topography accurately (Fig. 3). Buffer areas were surveyed with a greater density of points to capture the greater variation of topography within the buffer relative to the agricultural field area. Also, areas that visually appeared to receive surface runoff inputs were more intensively surveyed to identify the exact flow paths.

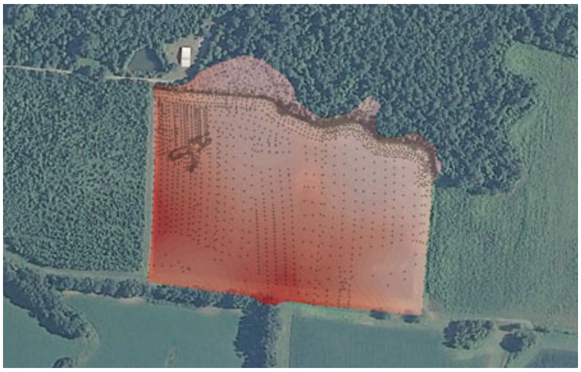

Fig. 3 In this figure of study sites 5 and 6, survey points have been overlaid with the 1 m × 1 m DEM of the agricultural field and buffer area. The color gradient, from *darker shade* to *light shade*, represents higher to lower elevation, respectively. Across both sites 4,080 individual survey points were collected. Points were collected with greater density in the buffer area and in areas that visually appeared to be important pathways for surface runoff

Survey points were converted to shapefiles using ArcGIS® 9.2 (ESRI 2006). Survey points were used to create triangulated irregular network (TIN) that were then converted to digital elevation models (DEM). DEMs were created for the entire area of each site (field and buffer) using 1 m × 1 m cells (Fig. 3). Variables for use in later analyses involving linear or area measurements were determined from the DEMs, while those involving volumetric measurements were determined from the TINs (Table 2).

The location of each CFP was identified visually during field surveys and corresponding survey points were labeled. Total scour length and volume were later

Table 2 Parameters calculated from total station survey data points at field scale study sites

Parameter measured	Units
Mean buffer width	m
Agricultural field area	ha
Buffer area	ha
Slope	%
Total scour length of CFPs	m
Total scour volume of CFPs	m^3
Berm volume	m^3
Mean berm height	m
Field area drained by CFPs	ha

calculated using these specific survey points as reference. Minor adjustments to CFP area were made in ArcGIS® since the Geographic Information System (GIS) more accurately quantifies these areas than visual observation in the field. Also during field surveys, the edge of the buffer, defined as the transition point where permanent vegetative cover begins and the cultivated field area ends, was noted. This line was used to identify field area, buffer area, and mean buffer width. Mean buffer width was calculated by dividing the total area of the buffer by the longitudinal distance (it covered) parallel to the buffer edge line. Slope of each study site was calculated as the average slope percent of the agricultural field area determined from the created DEMs.

The percent area of the field drained by concentrated flow was calculated using DEMs and the ArcGIS Spatial Analyst, Hydrology toolset. The toolset provides delineation of watersheds and flow networks based on a minimum number of cells included to create the feature (ESRI 1996). Using DEMs generated from total station survey points, drainage areas were delineated that contributed to each CFP identified in field surveys. The surface area of each drainage was then calculated from the total number of cells in each drainage area. Next, the drainage area of the smallest CFP identified in field surveys was used to calculate the relative percent of the field it drained by dividing the number of cells in the CFPs subwatershed by the number of cells in the entire agriculture field's drainage area. Ten percent was used at all sites as the minimum percentage of cells in the agriculture field that could potentially form an identifiable CFP. All drainages of at least this size were delineated. The Stream Network function in the Hydrology toolset was then used to generate all flow lines draining 10% of the field area of each site. These flow lines were then used to identify areas in the agricultural field where flow would concentrate. If flow was concentrated in the field area and entered the buffer in any of the minimum-sized watersheds in a field, they were identified as watersheds drained by concentrated flow. The total area of each watersheds meeting this criterion was then divided by the area of the field to obtain the percentage of the entire field that is drained by concentrated flow.

A line was plotted along the maximum berm accumulation points at each study site to analyze the pattern of berm accumulation. To identify this line at each site, 10 cm by 10 cm DEMs were generated representing the actual elevation and the base elevation of each buffer. Base elevation was determined by creating a DEM from points along the buffer edge and points along the stream bank. This method was developed to provide a best estimate of the original elevation (or base elevation) of each buffer before sediment accumulation occurred. The second DEM was generated from all the survey data points collected within each buffer to represent the elevation (or current elevation) at each site. Next, the DEM of current elevation was subtracted from the base elevation DEM to generate a third DEM representing the difference between actual elevation and base elevation at each site, allowing us to differentiate between areas of sediment accumulation (positive values) and scour (negative values). To delineate the points of maximum berm accumulation, contour lines were developed for each DEM based off the elevation range best suited to each individual buffer. Appropriate contour intervals for study sites ranged from 1 to 10 cm and were dependent on the level of detail needed to differentiate between areas of higher and lower elevation and the point spacing of the original survey data. From these contours, the best line of continuous higher elevation along the length of the buffer was delineated by manually plotting the points into a polyline. Discontinuous or isolated high points were not included on this line. Additionally, the distance from each point to the buffer edge was calculated to provide insight to the distance within the buffer that the berms formed. Figures were developed for each study site to illustrate the complexity and variability among berms formed within the buffers (Figs. 4, 5, and 6).

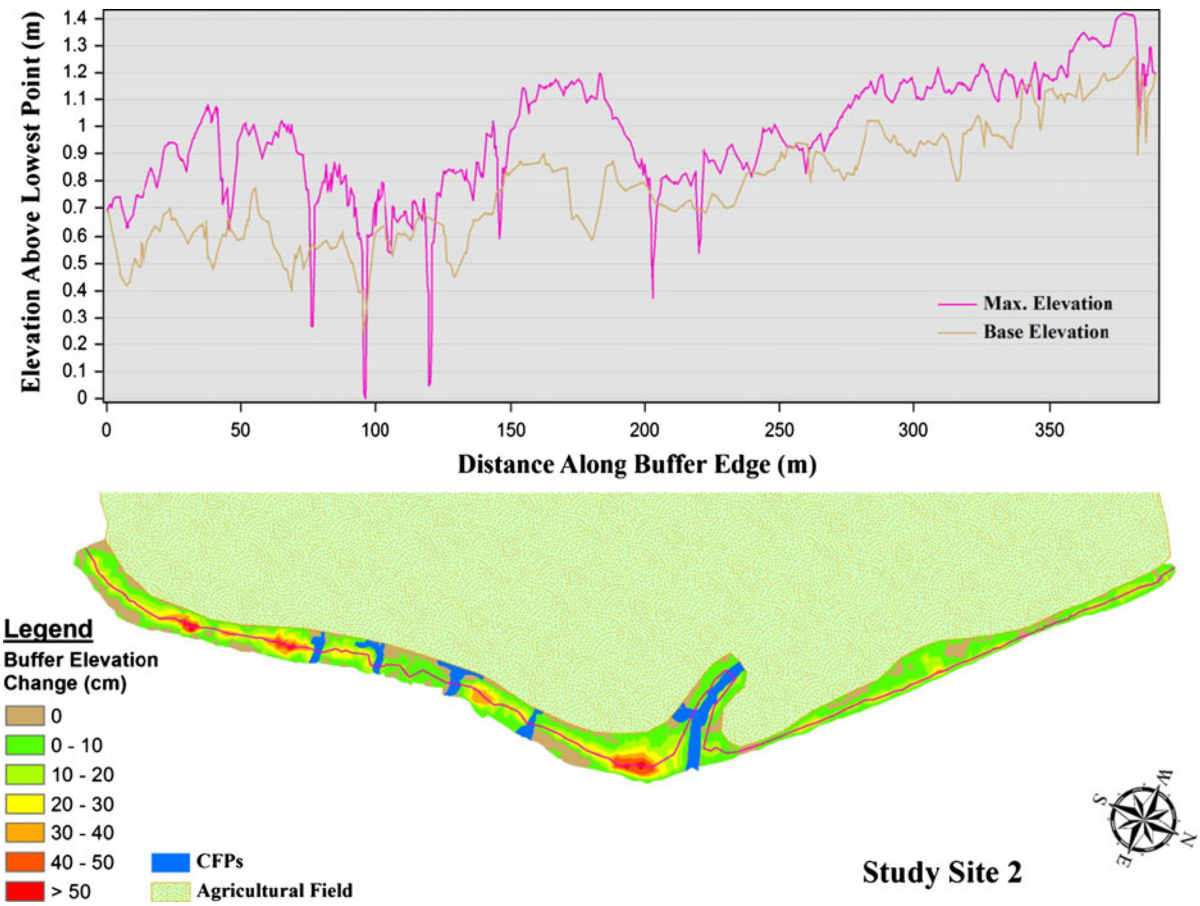

Fig. 4 Increases in elevation above the base elevation for Site 2. The adjoining *line graph* represents the line of maximum elevation within the buffer compared to the base elevation line. The graph has been scaled to match distance in the buffer diagram

Sediment berm sampling for soil texture

Soil texture was determined to attempt to identify the origin (i.e., from terrestrial sources or overbank flooding) of sediment accumulating within the buffers. Due to the selective process by which larger soil particles settle out of surface runoff sooner than finer particles (Alberts et al. 1981; Meyer et al. 1995), sediment coming from the agriculture fields (terrestrial sources) may result in coarser sediment at the field edge of the buffer and finer sediments toward the back of the buffer (Cooper et al. 1987; Lee et al. 2000). Conversely, sediment originating from overbank flooding should presumably result in the coarser sediments settling near the stream bank with finer sediments further into the field. Therefore, sand was chosen as the best indicator of significant deposition. Five random points were selected along the width of the ten riparian buffers and sampled for texture. At each random point, a transect line was established perpendicular to the buffer edge. Four points were then sampled in the following locations relative to the buffer edge: at 10 m out in the agriculture field, 1 m out in the agriculture field, at the buffer edge, and at 10 m in the buffer or on the stream bank, whichever was encountered first. Soil samples, containing approximately 150–200 g of soil, were composited from the upper 10 cm of soil taken at each transect point. Textural analyses were performed on air dried samples using the hydrometer method (Black et al. 1965).

Watershed scale analyses

Subwatershed selection and surveys

The Cache River basin in southern Illinois was also selected to conduct watershed scale studies of CFPs,

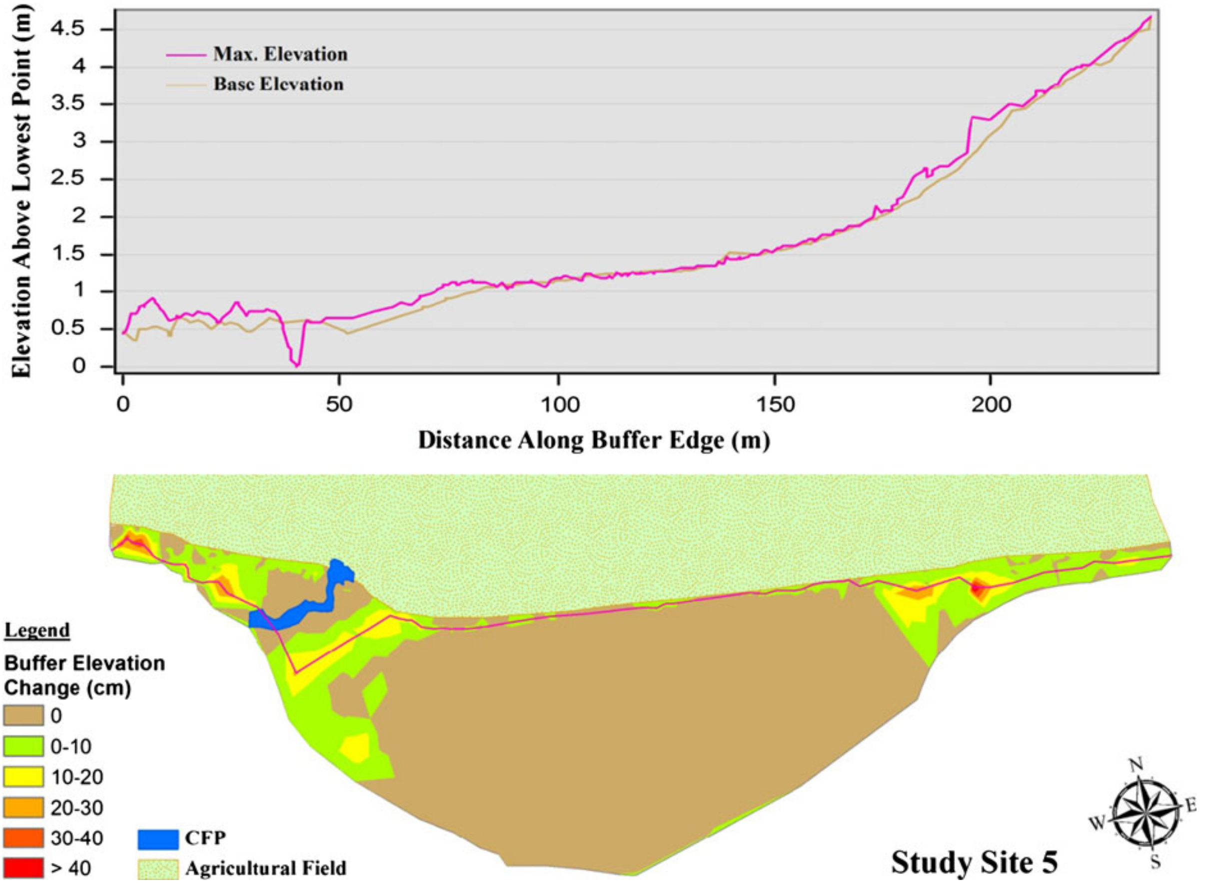

Fig. 5 Increases in elevation above the base elevation for Site 5. The adjoining *graph* represents the line of maximum elevation within the buffer compared to the base elevation line. The graph has been scaled to match distance in the buffer diagram

using the same three subwatersheds included in the field scale study. These watersheds are typical of southern Illinois, consisting of primarily agricultural land cover and a much smaller percentage of forested land cover.

Within each subwatershed, points were generated in ArcGIS at all road and stream intersections. Five locations were randomly selected from those points along intermittent and perennial stream channels. At each of the five sampling locations in each subwatershed, a stream-reach survey was conducted between July 2007 and September 2007. Stream reaches extended approximately 1,000 m downstream of each randomly chosen location, including both banks. Points where each significant CFP intersected the surveyed stream reach on either bank were noted using a Garmin® GPSMAP 60CSx GPS unit. Significant CFPs were defined as visually distinguishable flow paths that concentrated surface runoff from adjacent upland areas to the immediate floodplain of the stream being surveyed. The width and depth of each CFP as it entered the main stream channel was measured with a 100 m tape to estimate cross-sectional area. Buffer width was also recorded by pacing the width and rounding to the nearest 5 m. The type of CFP was classified as either a naturally occurring tributary, a CFP produced by erosional processes, or a constructed ditch created for drainage. Riparian buffer vegetation type and surrounding land cover type also were recorded at the location of each CFP.

Variable development

Width and depth measurements of CFPs measured during walking stream surveys were used to calculate a cross-sectional area for each CFP. Equation 1 was used to calculate CFP volume:

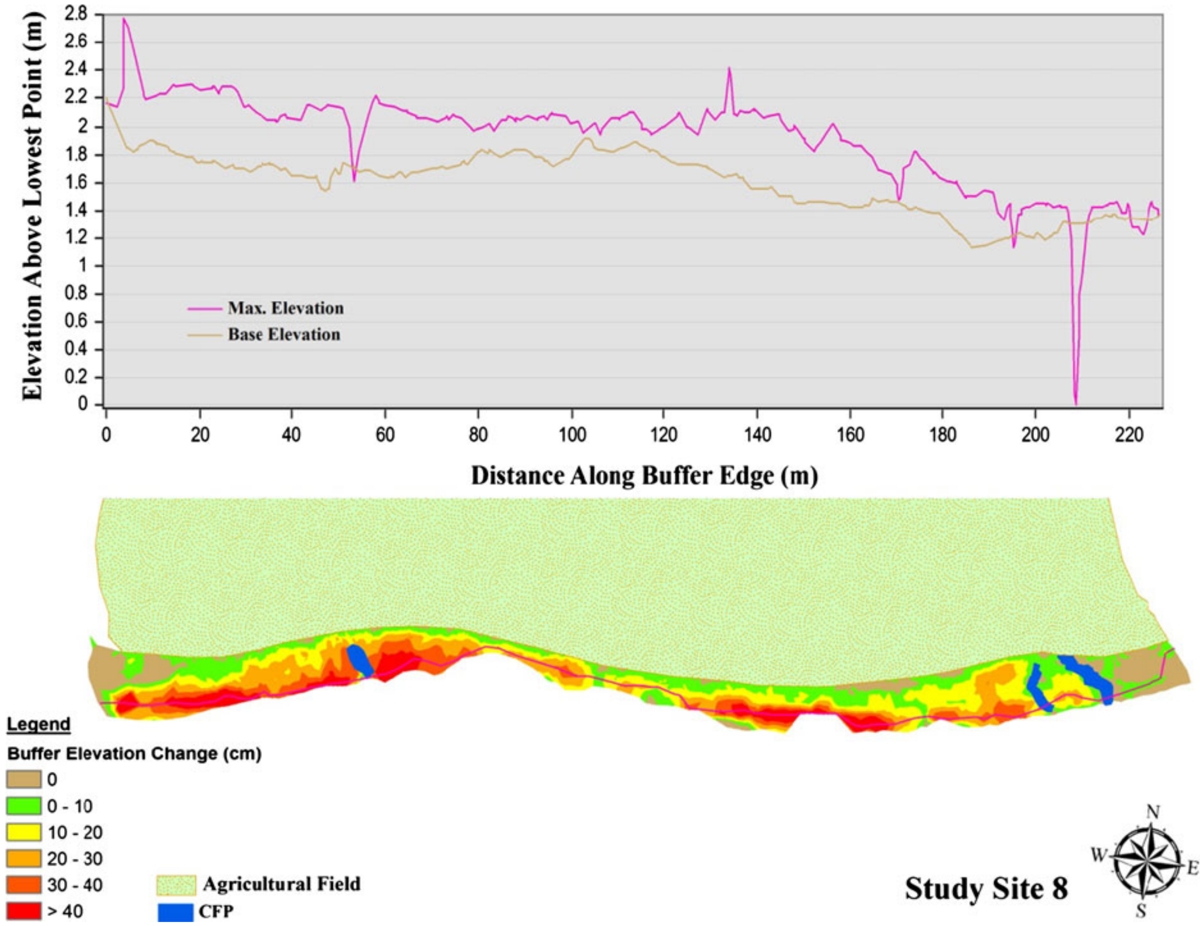

Fig. 6 Increases in elevation above the base elevation for Site 8. The adjoining *graph* represents the line of maximum elevation within the buffer compared to the base elevation line. The graph has been scaled to match distance in the buffer diagram

$$\text{CFP volume} = (\text{width} \times \text{depth})/2 \quad (1)$$

Since the majority of CFPs were triangular or trapezoidal in shape, the result was divided by 2 to account for bank slope and to calculate a more accurate estimate of volume, rather than simply multiplying width by depth.

To calculate the number of CFPs per kilometer of streams surveyed, CFPs were first categorized by land cover type and by subwatershed. Relative percentages of the land cover in each subwatershed were determined using ArcGIS® 9.2 and the 1999 Illinois Land Cover Dataset (US Department of Agriculture 2000). The 2007 National Agriculture Imagery Program aerial photos of the region were used to further verify the accuracy of the 1999 Illinois Land Cover Dataset and adjustments were made accordingly to account for discrepancies in the 1999 data. Streams surveyed were then analyzed in ArcGIS® to determine the land cover present in each stream survey. Land cover types for each stream were determined from field notes, the 1999 Illinois Land Cover Dataset, and 2007 National Agriculture Imagery Program aerial photos. Percent of land cover was calculated by determining the exact length of stream walked in each land cover type and then dividing that number by the total distance of streams surveyed. To determine the frequency of the CFPs per kilometer Eq. 2 was used.

$$\text{CFPs per km} = \text{Total \# of CFPs}/\text{km of Stream Surveyed} \quad (2)$$

Statistical methods

The sand portion of soil texture samples was compared by sampling location relative to the distance from the field/buffer edge and by tillage regime of the site. An arcsine transformation using an exponent of 0.3 was used to achieve normality (Sokal and Rohlf 1995) and provide more clarity in statistical tests (Roberts 2008) for mean percentages of sand. One-way analysis of variance (ANOVA) was used to test for differences in percent sand at the varying sampling locations across all sites. Two-way ANOVA was used to compare samples taken in fields under conventional tillage regimes to fields under conservation tillage practices. Differences, by tillage practice, in percent sand at the varying sampling locations were compared across all sites.

One-way ANOVA was used on land cover data from each watershed to compare the relative percentage of land cover in each watershed as a whole to the relative percentage of land cover surveyed in each stream survey. A separate one-way ANOVA was used to compare cross-sectional area values from CFPs in agricultural land or forested land cover. The cross-sectional area data were logarithmically transformed to achieve normality. The Kruskal–Wallis nonparametric test was used to test whether the number of CFPs in agricultural was different than the number in forested land cover since no transformation would normalize the data to meet assumptions of parametric tests.

Results

Field scale results

The texture of all soil samples was classified as silt loam based on the USDA Soil Texture Triangle (Soil Survey Division Staff 1993). Significant differences ($P = 0.05$) were detected in sand percentages among sampling locations (Fig. 7). Percent sand 10 m out in the field was significantly less than 10 m into the riparian buffer ($P = 0.01$). No other significant differences were detected.

Many of the attributes measured at field scale study sites showed considerable variation between sites (Table 3). Mean buffer widths varied from 8.9 to

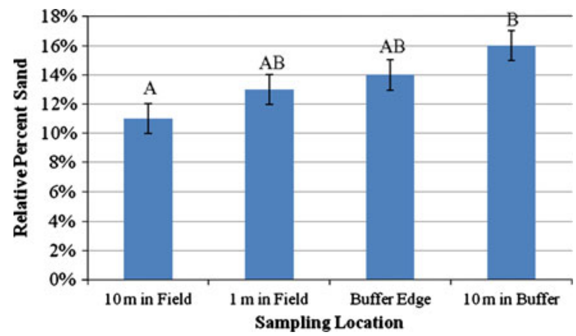

Fig. 7 Mean sand percentage by sampling location across all field scale study sites. Means with *different letters* are significantly different

38.7 m and CFPs occurred at buffer locations with width measurements ranging from 4.2 to 56 m. At least one CFP was identified at all sites and four sites had five CFPs. All CFPs identified in this study were in forest vegetation and none were identified in giant cane stands. Among the ten sites the percentage of field area drained by concentrated flow ranged from 82.5 to 100%. Eight study sites had more than 90% of the field area drained by concentrated flow and two sites had 100% of the field drainage identified as concentrated flow. At all study sites some accumulation of berm sediments was identified, with mean berm height ranging from 3 to19 cm (Figs. 4, 5, 6). Berm accumulation within buffers occurred at varying locations within the buffer, presenting no obvious deposition pattern identifiable from survey data.

Watershed scale results

The relative percentage of forest or agricultural land cover within each watershed, as determined by ArcGIS analysis, was not significantly different than those respective percentages assessed during walking stream surveys (forest $P = 0.32$, agriculture $P = 0.27$). Data collected during stream surveys identified at least one CFP in every stream reach surveyed. Measures of CFPs per kilometer were consistently higher for agricultural areas across all three watersheds (Table 4). Statistical analysis indicated that the total number of CFPs per kilometer was significantly greater for agricultural land ($P < 0.01$) compared to forested land. However, a comparison of the cross-sectional area of CFPs measured in forest and agricultural land did not show a significant

Table 3 Site attributes measured from total station survey data

Site	Field area (ha)	Buffer area (ha)	Mean buffer width (m)	Percent slope (%)	Total number of CFPs (#)	Field area drained by concentrated flow (%)
1	8.52	0.28	7.43	1.08	5	90.60
2	3.45	0.28	8.51	4.68	5	94.70
3	3.21	1.07	38.70	7.13	5	96.00
4	0.89	0.46	33.64	7.20	5	82.50
5	4.22	0.65	27.77	4.52	1	85.50
6	2.91	0.22	10.12	3.89	2	97.80
7	1.87	0.26	10.97	5.52	2	100.00
8	1.63	0.19	8.86	6.12	2	99.60
9	3.69	0.54	20.93	0.73	1	98.50
10	4.58	0.27	10.79	1.14	1	100.00

Survey points were analyzed using ArcGIS® to calculate values in this Table

Table 4 Results from walking stream surveys of three watersheds of the Cache River basin, southern Illinois

Watershed	Land cover type	Length surveyed (m)	Total CFP cross-sectional area (m^2)	Mean CFP cross-sectional area (m^2)	CFPs per kilometer
Big Creek	Agriculture	6,714	53.35	1.14 (± 2.23)	7.95
	Forest	1,768	5.26	1.46 (± 0.88)	2.97
Cypress Creek	Agriculture	5,894	188.15	4.59 (± 14.93)	31.92
	Forest	1,316	1.02	0.34 (± 0.12)	0.78
Mill Creek	Agriculture	8,337	23.25	1.22 (± 1.88)	2.79
	Forest	988	0.00	0.00	0.00

Surveys were conducted on randomly selected stream reaches from July to September 2007

difference ($P = 0.76$). A much larger number of CFPs were found in forested buffers compared to buffers with giant cane and herbaceous vegetation (Table 5).

Discussion

Field scale

Our study has demonstrated that CFPs are common within the riparian buffers we examined. CFPs were observed within buffers widths of 4.2–56 m and appeared to be primarily produced through surface runoff from the adjacent agricultural field, although several CFPs had no identifiable contributing watershed within the field, suggesting other hydrologic processes influenced their development. High percentages (82.5–100%) of all agricultural fields in this study were found to drain surface runoff via concentrated flow. In most cases, the field area consisted primarily of one or two watersheds that contributed surface runoff to a single CFP (Site 2 and Sites 5–10). Surprisingly, very little of the field areas (0–17.5%) included in our surveys contributed drainage at the buffer edge which we could classify as sheet flow, although to some degree sheet flow was present upslope in every watershed. This result is quite extraordinary, indicating that large volumes of surface runoff from each agricultural field area are reaching streams via concentrated flow, offering adjacent riparian buffers little or no opportunity to provide filtration. Further, no research to date precisely quantifies the agricultural field area drained by concentrated flow through riparian buffers. Dosskey et al. (2002) developed a method of visual assessment to identify field areas drained by concentrated flow, but did not provide quantifiable measurements. Others have reported visual observance of concentrated flow, but also provide no quantification of the field area contributing to

Table 5 CFP size and occurrence as measured in walking stream surveys

Riparian buffer vegetation	Mean cross-sectional area (m^2)	Total number of CFPs
Forest	2.531 (±3.954)	103
Giant Cane	2.154 (±2.090)	9
Herbaceous	1.403 (±2.895)	12

These values are divided into the three categories of riparian buffer vegetation identified during surveys

Fig. 8 Sediment berm deposition from overbank flooding is shown here. This picture was taken during a walking stream survey a few days after a large storm event. There is a stream and riparian area to the *right* and a densely vegetated pasture to the *left*. Also visible in the picture are large amounts of corn residue, deposited from an upstream source during the same storm event providing an additional indication of flooding

concentrated flow (Dillaha et al. 1989; Daniels and Gilliam 1996; Knight et al. 2010).

At all of our field scale study sites, forest was the dominant buffer vegetation type, although some small stands of giant cane were present. Cane stands varied in size, but were typically very dense, limiting forest encroachment. Some herbaceous groundcover was present at all sites in varying density, but did not predominantly occupy any buffer areas. CFPs identified at all study sites only occurred through forest vegetation and there were no CFPs identified in giant cane stands. In several instances, CFPs occurred at the giant cane/forest transition point, but never directly breached a canebrake. These results suggest that giant cane may have greater resistance to CFPs compared to trees.

During watershed scale stream surveys, nine CFPs were recorded within cane stands, indicating that cane has some susceptibility to CFP formation. However, these nine CFPs only accounted for 7% of all CFPs recorded during stream surveys. At our field scale sites, all of the cane stands observed were extremely dense full-sun stands, whereas some cane stands in the watershed scale surveys were mixed with forest, partially shaded and less dense. This relationship could explain why some of the CFPs identified in watershed scale study were located in cane, since less dense stands of cane would presumably provide less of the runoff inhibiting properties identified by Schoonover et al. (2005, 2006). A recent study by Knight et al. (2010) provided further evidence of grass buffer species' resistance to concentrated flow. Results identified forested buffers with a grass filter strip installed at the field edge provided superior resistance to CFPs compared to buffers with grass absent. Similar to Knight et al. (2010), cane stands at our field scale study sites were positioned at the buffer edge and would provide comparable interception of incoming surface runoff. They attributed greater buffering of concentrated flow to a combination of greater buffer width (due to the added grass filter) and the physical properties of the grass (Knight et al. 2010).

Sediment is generally deposited in larger amounts near the front edge of the buffer (Schultz et al. 2009), exemplified by relatively narrower buffers that trap large amounts of sediment (Daniels and Gilliam 1996; Robinson et al. 1996; Lee et al. 2000). Therefore, we hypothesized that sediment accumulation at the buffer edge could produce low berms that would increase the risk of CFP development in riparian buffers by restricting the occurrence of sheet flow through the buffer. Cooper et al. (1987) measured sediment deposition across riparian areas. In their study, the largest amount of sediment deposition was observed in the forest edge locations, with accumulations of 15–30 cm over 20 years. Schmitt et al. (1999) reported a large majority (76–89%) of sediment reduction within the first 7.5 m of buffer. Results from our soil texture analyses were not consistent with this depositional pattern. Larger particles made up greater portions of the soil sampled further back in the buffer, or closer to the adjacent stream, which is indicative of deposition occurring in the opposite progression (i.e., from the stream out to field area, see Fig. 8) since larger particles tend to be deposited first (Alberts et al. 1981; Meyer et al. 1995). This depositional pattern implies that overbank flooding may be responsible for depositing sediment within the buffer areas. This pattern of deposition has been noted as a secondary means of deposition with riparian buffers (Schultz et al. 2009). After analysis of field survey data points, berm accumulation patterns at several study sites have occurred toward the back of the buffer (Figs. 4, 5, 6). However, the areal extent of berms has not presented a defined pattern across all sites, though considerable accumulation is present at all sites. Additionally, there was no clear depositional pattern that would relate berm location to CFP location within the buffer.

Research suggests that the processes described in our conceptual model can lead to reduced filtering abilities in buffers. Dosskey et al. (2002) found that CFPs reduced sediment attenuating abilities of riparian buffers in Nebraska when field collected data were analyzed using the VFSMOD model. They also observed the presence of sediment berms at the field edge, which forced runoff to flow parallel to buffers until a low point was breached. Dillaha et al. (1989) found that buffers receiving runoff from areas with less slope tended to trap sediment more efficiently. In several cases, they identified relatively new buffers (1–3 years) that had trapped a large amount of sediment, bringing the buffer elevation higher than the field. They reported that these buffers tended to force surface runoff to flow parallel to the buffer until reaching a low point and concentrating. This is very similar to the processes that appear to be responsible for berm formation in our study and demonstrates an important temporal relationship. Our findings and those of Dillaha et al. (1989) show that it is possible for a riparian buffer to function as a highly effective sediment trap. Attenuating enough sediment that buffer elevation is increased and flow concentration is promoted, subsequently introducing a new threat to water quality by providing the opportunity for a CFP to develop. Consequently, this point illustrates the difficulty in maintaining efficient buffer function over the long term.

Buffer width has been an important metric related to buffer design and effectiveness. Mean buffer width at our sites ranged from 7.43 to 38.70 m and did not appear to impact the development of multiple CFPs per site. There were 5 CFPs at the narrowest site (Site 1) and 5 CFPs at the widest site (Site 3). However, other research has shown that narrower forested buffers have a greater susceptibility to the development of CFPs (Knight et al. 2010). Knight et al. (2010) observed remnant forested buffers with a mean width of 17.9 m. They found a mean width of 12.8 m among buffers with CFPs. In our field scale study, the mean buffer width was 17.8 m across all sites and all of our buffers had at least one CFP. At specific CFP locations, the mean buffer width was 24.7 m. Our data suggests that CFPs in similar remnant forest stands can develop at greater widths than those reported by Knight et al. (2010).

Of the 29 CFPs measured in our study, only nine did not completely pass through the buffer. Upon further investigation into the field attributes associated with the CFPs, it was discovered that five of the nine had no identifiable drainage area within the agricultural field or riparian buffer. This observation indicates that surface runoff originating within the agricultural field area is not responsible for formation of these CFPs. With no identifiable drainage area in the field area, the only opportunity for water and erosion to create these CFPs would come from either overbank flooding of the adjacent stream, or flooding of adjacent small depressions resulting in flow parallel to the buffer within the agricultural field itself. Shallow surface runoff associated with typical storm events would presumably not have the potential to reach these CFPs in any significant quantity. Another interesting observation from these data is that four additional CFPs had no appreciable drainage area, but did reach the stream channel. In this instance, overbank flooding and scour could be responsible, as well as headcut migration from the adjacent incised stream. Most streams typical of southern Illinois agricultural watersheds exhibit a great degree of incision from decades of drainage alteration and streams adjacent to all of our study sites are no exception (Illinois Department of Natural Resources 1997a).

It is important to note that the aforementioned nine CFPs were the minority in our dataset, but they do provide examples of hydrologic processes at work that riparian buffer design does not typically account for. These and other CFPs in our field scale analysis were compared to measured field attributes in order to identify possible relationships. However, these relationships were a result of hydrologic processes that occur over many seasons and the physical characteristics we measured were only a snap shot in time. Our approach was designed to very accurately measure field characteristics at the moment of survey.

However, we lacked specific data on temporal change in field attributes, streamflow, rainfall, and the varying hydrologic processes that act upon riparian buffers. For example, berm formation at the field edge is a result of a more continuous process. Every precipitation event that results in surface runoff offers some opportunity for sediment to accumulate within the buffer, whereas sediment accumulation from overbank flooding is a more discrete process. A significant flooding event must occur for any opportunity of measurable accumulation. In our analyses, we were unable to clearly identify the process (surface runoff, overbank flooding, or a combination of both) driving the berm formation.

Watershed scale

There is a significant need for research that can better quantify the relationship between water quality and riparian buffers beyond the plot scale (Dosskey 2001). The watershed scale portion of this study was designed to take a broader look at CFPs, beyond the field (or plot) scale and provide complementary results to the field scale study. Objectives of this portion of the study were to identify the prevalence and size of CFPs based on riparian buffer vegetation, riparian buffer width, and the type of land cover present. Results from this data collection indicated that CFPs were prevalent across all three watersheds occurring at a rate of one CFP per 7.7 km of survey.

Statistical analysis of CFPs per kilometer of stream surveyed indicated that a significantly greater number of CFPs occurred in agricultural areas then forested land. Since a greater amount of surface runoff is typically expected from agricultural areas versus forested areas, one may assume a greater potential for CFP formation. Therefore, it is not surprising that agricultural areas produce significantly more CFPs per kilometer of stream than those receiving runoff from forested areas. It is, however, less intuitive to find that cross-sectional areas do not differ significantly as well. Greater volumes of surface runoff would presumably create CFPs with greater cross-sectional area. Nonetheless, cross-sectional areas were not different between the two land cover types. Agricultural areas simply have more CFPs conducting surface runoff, which allows them to handle the larger runoff volumes associated with this type of land use. However, it is more likely for CFPs draining agricultural areas to have a greater potential to contribute to water quality impairments since agricultural surface runoff generally contains higher nutrient, chemical, and sediment levels than forested areas.

Results from the watershed scale analysis provide supporting data to the findings of our field scale study. Throughout the three watersheds of the Cache River CFPs were consistently identified in 1,000 m stream surveys. These data, coupled with field scale data identifying at least one CFP per individual agricultural field provide evidence that the occurrence of CFPs is widespread in agricultural areas and riparian buffers across the Cache River watershed.

Conclusion

This study has identified a substantial presence of CFPs within three watersheds in southern Illinois. At field scale study sites, at least one CFP was measured at each site. Additionally 82.5–100% of the agricultural field areas at all study sites were found to drain through riparian buffers in the form of concentrated flow. Watershed scale study results provide further support that CFPs are a common occurrence within the southern Illinois watersheds included in this research. If similar conditions are found in other primarily agricultural watersheds in the US, CFPs will present a significant challenge for land managers concerned with water quality, since CFPs most likely suppress or eliminate the filtering capacities of riparian buffers and add to soil loss as the CFP incises. Further research is needed to identify the impact that CFPs may have on water quality in order to assure that the implementation of riparian buffers as a conservation practice is effective.

In both our watershed scale and field scale studies, CFPs were identified in considerable numbers, implying that riparian buffer function is decreasing over time. Management of riparian buffers for water quality needs to address the long term performance of these buffer systems. Long-term maintenance plans need to be developed to increase the life span of riparian buffers and improve their effectiveness as filters of surface runoff. With further research and increased attention from land managers, riparian buffers will provide benefits to water quality over the long term.

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