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The stream channel incision syndrome and water quality

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ABSTRACT

Watershed development often triggers channel incision that leads to radical changes in channel morphology. Although morphologic evolution due to channel incision has been documented and modeled by others, ecological effects, particularly water quality effects, are less well understood. Discharge, basic physical parameters, solids, nutrients (nitrogen and phosphorus), chlorophyll and bacteria were monitored for five years at two sites along a stream in a mixed-cover watershed characterized by rapid incision of the entire channel network. Concurrent data were collected from two sites on a nearby stream draining a watershed of similar size and cultivation intensity, but without widespread incision. Data sets describing physical aquatic habitat and fish fauna of each stream were available from other studies. The second stream was impacted by watershed urbanization, but was not incised, so normal channel–floodplain interaction maintained a buffer zone of floodplain wetlands between the study reach and the urban development upstream. The incised stream had mean channel depth and width that were 1.8 and 3.5 times as large as for the nonincised stream, and was characterized by flashier hydrology. The median rise rate for the incised stream was 6.4 times as great as for the nonincised stream. Correlation analyses showed that hydrologic perturbations were associated with water quality degradation, and the incised stream had levels of turbidity and solids that were two to three times higher than the nonincised, urbanizing stream. Total phosphorus, total Kjeldahl N, and chlorophyll a concentrations were significantly higher in the incised stream, while nitrate was significantly greater in the nonincised, urbanizing stream ($p \leq 0.02$). Physical aquatic habitat and fish populations in the nonincised urbanizing stream were superior, as it supported almost twice as many species and yielded more than four times as much biomass per unit of effort. These results suggest that channel incision is associated with a complex of ecological stressors that includes channel erosion, hydrologic perturbation, and water quality and physical habitat degradation. Ecological engineering of stream corridors must focus at least as much energy on mediating hydrologic perturbations and managing habitat quality as on pollutant loadings.

1. Introduction

The magnitude, nature and significance of the impact of human activities on stream water quality are of growing concern. A national assessment of wadeable streams in the U.S. found that 42% of stream miles were in poor condition, with the most widespread stressors identified as nitrogen (N) and phosphorus (P), streambed sediments, and riparian disturbance (Paulsen et al., 2006). Almost one-third of streams had high N and P concentrations relative to regional reference sites. Another national assessment reported that 60% and 78% of about 130 sampled streams had average annual flow-weighted concentrations of NO_3^- and total N, respectively, exceeding 2 mg L^{-1} (Hamilton et al., 2004). About 85% of these streams had average annual flow-weighted total P concentrations of at least 0.1 mg L^{-1}. Analysis of nutrient data from 481 sites collected between 1992 and 2001 indicated that U.S. EPA regional nutrient criteria for total N were exceeded at 96% of sites that drained either urban, agricultural or mixed-use watersheds and that criteria for total P were exceeded at 97% of sites (Mueller and Spahr, 2006).

Biological communities in wadeable streams exhibit levels of degradation similar to those reported for chemical quality, with about 42% of streams included in the national assessment yielding benthic indices in a category rated "most disturbed" (Paulsen et al., 2006). The diverse stream fauna of the southeastern U.S. are apparently experiencing accelerated extinction rates (Ricciardi and Rasmussen, 1999; Warren et al., 2000) due to habitat and water quality degradation (Karr et al., 2000; Warren et al., 2000). A recent assessment of the status of freshwater fishes identified 39 threatened, vulnerable or endangered species in the Mississippi Embayment ecoregion (Jelks et al., 2008).

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With such reports of extensive environmental degradation of streams, information regarding links among physical, chemical and biological stream quality is needed to make stream management decisions such as setting TMDLs and other regulations (Lee and Jones-Lee, 2008). Are stream ecological services most efficiently managed by channel erosion controls, riparian zone plantings, or watershed treatments to control pollution from point or nonpoint sources? Work by others has provided insights regarding chemical water quality in agricultural watersheds where hydrology is dominated by tile drainage or irrigation (Capel et al., 2008). Much work has also been done to document the syndrome of stream degradation that often accompanies watershed urbanization (e.g., Hamer, 1972; Henshaw and Booth, 2000; Nelson and Booth, 2002; Davis et al., 2003; Morse et al., 2003; Brett et al., 2005; Konrad and Booth, 2005). However, less information is available for mixed-cover, rural watersheds with simple surface drainage.

Streams draining such watersheds are often plagued by a syndrome that prominently features channel incision. Incision may be triggered by channelization (Simon, 1989), but may also be triggered by land use changes that increase peak flows or reduce sediment supply (Galay, 1983). Since incised channels are straighter, steeper and often wider, larger flows are contained within the channel, leading to flashier flows and reduced hydraulic retention (Shields and Cooper, 1994; Doyle and Shields, 1998; Bledsoe and Watson, 2001; Stofleth et al., 2007). Stream–floodplain interaction is eliminated or greatly reduced, and floodplain wetlands are often dewatered, cleared, filled or destroyed by channel erosion. Channel erosion driven by incision accounts for 60–90% of sediments leaving many of these watersheds (Shields et al., 2009a), and some experience annual sediment yields that are twice the national average (Shields et al., 1995). In such systems, stream turbidity, suspended solids and phosphorus concentrations are uncoupled from watershed conditions and are driven by instream hydrologic processes (Schlosser and Karr, 1981). Some workers have suggested that incision and similar processes that reduce instream carbon, contact time between water and benthos, and connections between the stream and adjacent terrestrial habitats or carbon-rich soils elevate N export from smaller streams (Schilling et al., 2007; Stofleth et al., 2007; Craig et al., 2008; Shields et al., 2008). Habitats of incised streams tend to lack stable pools, large wood and stable substrate, leading to elimination of longer lived large-bodied predator fishes in favor of smaller opportunists (Shields et al., 1994). This paper seeks to evaluate the associations among incision, hydrology, and water quality by comparing a deeply incised, biologically degraded stream to a nonincised, less-impaired stream draining a similar nearby watershed. Estimates of annual loads of solids, N and P are computed and compared to published values for agricultural watersheds in other regions.

2. Sites

Typical stream reaches were selected for study within two watersheds with similar topography and soils (USDA, undated) located about 80 km apart in the Yazoo River basin in northern Mississippi (Fig. 1). One reach, Little Topashaw Creek (LTC), was experiencing extreme incision and attendant erosion of channel banks. In contrast, the study reach of Toby Tubby Creek (TTC) was stable. Contributing watersheds had similar land use, except that the LTC watershed was about 70% forested, while TTC was only about 45% forested due to urbanization in its headwaters (Table 1). The history of watershed management was similar for the two sites. European settlement of the area began about 1830 and was followed by deforestation, cultivation, rapid erosion of hillsides, and accelerated valley sedimentation (Happ et al., 1940). Valley bottoms were covered by up to several meters of sediments eroded from hillslopes (Happ et al., 1940; Grissinger and Murphey, 1982),

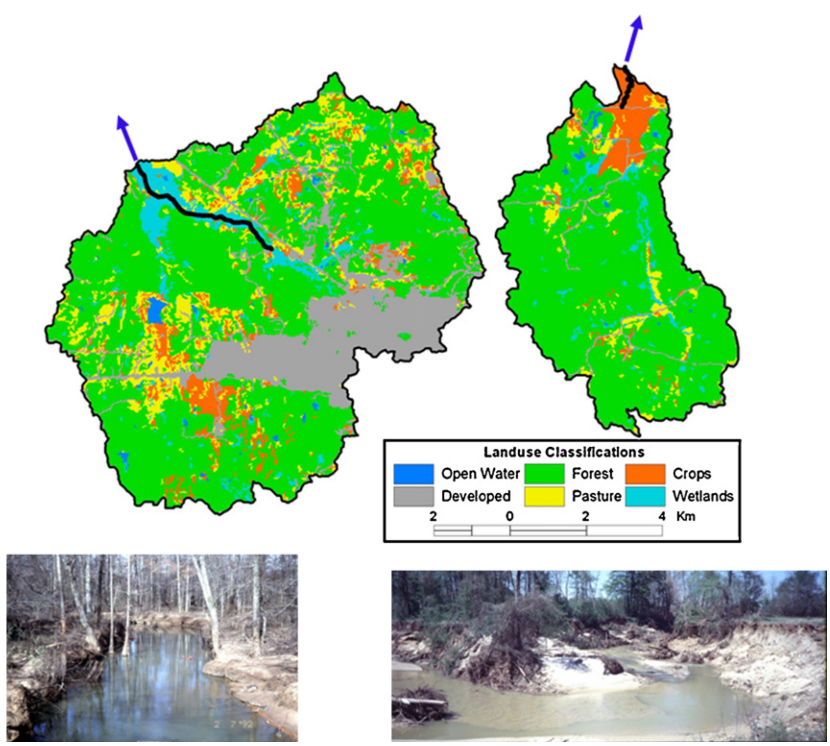

Fig. 1. Toby Tubby Creek (left) and Little Topashaw Creek watershed land use. Heavy black lines near the top of each map indicate study reaches. Watershed boundaries were delineated using AGNPS tools (http://www.wsi.nrcs.usda.gov/products/w2q/h&h/tools_models/agnps/index.html) developed within the ArcView3.x software and DEM information from the National Elevation Dataset (http://seamless.usgs.gov/). Land use was taken from the National Land Cover Dataset 2001 http://seamless.usgs.gov/). Blue arrows indicate outflows from watersheds. Photographs show typical conditions in study reaches.

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Table 1
Characteristics of study reaches at their upstream and downstream ends.

	Little Topashaw Creek LTC		Toby Tubby Creek TTC	
	Upstream	Downstream	Upstream	Downstream
Watershed size, km^2	25	34	20	81
Land use, %				
Cropland	5	7	3	6
Pasture or grassed	6	6	5	10
Shrub/scrub	13	13	10	15
Forest	72	70	43	47
Developed	3	3	39	19[a]
Wetland or water surface	1	1	0	1
Impervious	0	0	1.1	0.26
Channel evolution model (Simon, 1989) stage	III	IV/V	I	I
Length, km	2		5	
Sinuosity	2.1		1.3[b]	
Slope	0.002		0.002[b]	
Bed material size, D84, D50, D16, mm	0.95, 0.37, 0.16		0.38, 0.30, 0.06[b]	
Mean channel top width, m	35		10[b]	
Mean channel depth, m	3.6		2[b]	

[a] About half of the area in TTC classified as “developed” was classified as “developed open space.” About 1% was classified as “high intensity development.”
[b] These TTC reach characteristics based on surveys and samples of the downstream 1 km of the 5 km reach.

and swampy conditions developed as channels filled with sediment. Landowners, acting as individuals and through drainage districts, attempted to reclaim valley lands by channelizing streams and constructing drainage ditches.

2.1. Little Topashaw Creek, a rural incising stream

Little Topashaw Creek watershed topography was characterized by relatively flat (<2%) alluvial plains along streams and fairly steep (>12%) forested hillslopes. Maximum watershed relief was about 80 m. Row-crop agriculture (sweet potatoes, cotton, corn, soybeans) was limited to the alluvial plains bordered by forested hillslopes. Subsurface flow was common, and water perched by clay layers eroded the highly conductive sandy layers above as it emerged from the steep stream banks (Wilson et al., 2007). Available evidence suggests the LTC channel in the study reach incised 4–5 m and width increased by a factor of four to five between 1955 and 2000 due to downstream channelization (Simon and Thomas, 2002). The reach was also impacted by channelization of upstream reaches, with evidence of channel straightening in the watershed occurring as early as 1913. During this study (1999–2004) channel morphology was typical of stages III, IV and V of the channel evolution model of Simon (1989) (Simon and Thomas, 2002; Wallerstein, 2000): concave banks on the outside of meander bends failed by mass wasting and sand accreted on large point bars opposite failing banks. Outside of bends, eroding banks encroached on adjacent cultivated fields. Bed degradation continued in the upstream half of the study reach during the study; one 0.6 m high headcut advanced about 60 m upstream during one flow event, and the mean thalweg elevation for the entire reach decreased about 0.5 m over the course of the study (Shields et al., 2004). Two large meanders were eliminated by chute cutoffs during the course of the study. The study reach was used as a stream corridor rehabilitation research and demonstration site with construction in 2000 (Cooper et al., 2004; Dabney et al., 2004; Shields et al., 2004, 2006, 2008, 2009a,b; Martin et al., 2005; Smith et al., 2006; Pezeshki et al., 2006; Stofleth et al., 2007). Initial effects of structures on channel stability were positive, but rehabilitation measures were generally ineffective in controlling channel instability over the longer (∼5–6 years) term.

Levels of 17 pesticides reported for water samples collected from LTC during storm events in 2000–2004 (Smith et al., 2006) were typically greater than those reported for another hill land stream, Otoucalofa Creek (Knight and Cooper, 1996) and oxbow lakes in the intensively cultivated Mississippi Delta (Cooper et al., 2003; Zablotowicz et al., 2006; Moore et al., 2007; Smith et al., 2007), showing the impact of agriculture on water chemistry within the LTC study reach despite cultivated land use being <7% of the total watershed. The LTC fish population was dominated by small-bodied, rapidly reproducing opportunists typical of warmwater streams disturbed by incision (Shields et al., 1998), and was generally inferior to TTC (Table 2 and Shields et al., 2006).

Table 2
Characteristics of baseflow fish and physical habitat collections from study reaches of Toby Tubby Creek (TTC) and Little Topashaw Creek (LTC).

	TTC, 1991–1995	LTC, 1999–2004
Total no. of species, all samples	48	27
Total no. of species listed as imperiled (Jelks et al., 2008)	1	0
Total nos. of tolerant/intolerant species	6/7	3/2
Mean fish catch biomass, g/150 m	1080[a]	279
Mean of lengths of largest individual in each sample, cm	32	12
Mean % of catch biomass comprised by cyprinids	<1	64
Mean % of catch biomass comprised by centrarchids	70	26
Mean baseflow water depth, cm	45	6/11[b]
Mean fraction of bed covered with organic litter, %	20	5
Mean bed sediment carbon, %	0.26	0.13

[a] Based on 1993–1995. Mean for 1991–1992 was about four times higher, perhaps due to prolonged regional flooding in early 1991 (Shields et al., 1998).
[b] Before and after addition of large wood structures (Shields et al., 2006).

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2.2. Toby Tubby Creek, an urbanizing stable stream

Toby Tubby Creek was a sinuous, sand-bed stream flanked by forested wetlands (Fig. 1). Maximum watershed topographic relief was about 105 m. Watershed topography was characterized by alluvial plains and wetlands along streams and fairly steep (>12%) forested or urbanized hillslopes. Urbanized slopes, of course, had been graded and modified by the addition of drainage features such as sewers, culverts and ditches. Contributing impervious area for the TTC reach (Table 1) was well below the 10% threshold suggested by Wang et al. (2000) in their study of urbanization impacts on fish in small Wisconsin streams and the even more stringent criteria suggested based on Georgia (Wenger et al., 2008) and Maine (Morse et al., 2003) streams. The primary crops grown were cotton and soybeans, and soils were acidic and dominated by loess or loess-derived alluvium and sand. Row-crop agriculture was limited to the alluvial plains, which also supported pasture, fallow fields, and developed land uses.

Beaver dams and associated ponds were common within the TTC study reach floodplain and were occasionally found within the main channel. The main channel was moderately sinuous, but most tributary streams were straightened several decades ago. Evidence of frequent overbank flow (trashlines, sediment deposits, etc.) was common within the wetland corridor. Three years of limited seasonal water quality data showed TTC levels of dissolved solids, nutrients, and conductivity were intermediate to those from a pristine watershed nearby and a more highly urbanized watershed contiguous to TTC (Lizotte et al., 2002). The stable TTC physical habitat was distinct from the incising LTC with greater baseflow depths, higher levels of large wood density and bed sediment carbon content (Table 2). TTC produced nearly twice as many fish species and more than four times as much fish biomass per unit of sampling effort during five years of semiannual sampling (1991–1995) than LTC did during six years (1999–2005) (Table 2). Furthermore, TTC was dominated by centrarchids and had more predators and larger individuals (Shields et al., 2006, 2008). In our analysis below, LTC serves as a treatment site since it is perturbed by severe channel erosion, while TTC serves as a nonincised reference.

3. Methods

3.1. Data collection

Precipitation was measured at LTC by tipping-bucket rain gages located at each end of the study reach during the period 1999–2005. LTC tipping-bucket data were used to compute monthly and annual precipitation totals. Hourly precipitation totals were obtained for a centrally located site within the TTC watershed for 1991–2005 from the National Climatic Data Center and used to compute monthly and annual totals for this watershed.

Stream stages were recorded at 15 min intervals during water years 2000–2005 at the upstream end of the LTC study reach using an acoustic Doppler system that included a pressure transducer. Stages were converted to discharges using a rating curve based on the velocities measured using the Doppler instrument, application of a uniform flow formula, and surveys of channel slope and cross-section. Channel geometry was resurveyed at 3–12-month intervals throughout the study. Missing data were replaced using flow values reported for a downstream gage by the U.S. Geological Survey (07282075—Topashaw Creek Canal near Hohenlinden, MS), adjusted using a site-specific regression formula. Stage records were collected at 15 min intervals during water years 1993–1996 near the downstream end of the TTC reach using an ultrasonic water level sensor system. TTC stages were manually measured concurrently with water grab sample collection during 1991–2004.

Little Topashaw Creek water quality samples were collected for five to nine days each month during 1999–2005 at two sites that bracketed the study reach using ISCO 2700 or 3700 automated samplers. In addition, logging monitors (YSI 6000 or YSI 6600) were concurrently deployed with the automated samplers and were used to measure temperature, conductivity, pH and dissolved oxygen every 30 min *in situ*. At TTC, water samples and *in situ* readings were collected monthly from sites that bracketed the TTC study reach during 1991–2003. Water samples from both streams were preserved via chilling and transported to the laboratory for analysis. Physical and chemical water parameters consisting of hardness (EDTA titrametric method), alkalinity (titration method), turbidity (calibrated Hach electronic turbidimeter), total solids (TS), dissolved solids (DS, dried at 180 °C), total ammonium-N (phenate method), total NO_3-N (cadmium reduction method), total NO_2-N (colorimetric method), total N [NO_3-N + NO_2-N + total Kjeldahl N (block digestion and flow injection analysis)], soluble (filterable) P (ascorbic acid), total P (persulfate digestion + ascorbic acid), chlorophyll a (pigment extraction and spectrophotometric determination), fecal coliforms (membrane filter technique), and enterococci (membrane filter technique) were analyzed using standard methods (APHA, 1998).

3.2. Data analysis

Annual and seasonal precipitation means were computed for each watershed. Hydrologic regimes for the two streams were characterized by computing mean daily discharges for LTC and mean daily stages for both streams using the periods of record. LTC discharges were used to compute the Richards–Baker flashiness index (Baker et al., 2004). For comparability, stage series were resampled at daily intervals and linearly transformed so that the minimum observed stage for each stream = 0.0 m. Stages from both streams were used to compute the entire suite of indices of hydrologic alteration proposed by Richter et al. (1998), but only selected parameters are considered below. All water quality data for all sites were subjected to exploratory analyses in the form of summary statistics and time series plots. However, since the data were collected at different frequencies over different periods, a subset of the LTC data was used for statistical testing. Specifically, the portion of the LTC database concurrent with the TTC period of record (1999–2003) was sampled randomly to produce a subset with each calendar month represented by only one sample. Effects of in-channel construction activities (building large wood structures for stream restoration) at LTC during the summer of 2000 were assessed by computing the differences in each water quality variable (downstream − upstream) for the construction period (July–August 2000), and for the same months for years before and after the year 2000. Nonparametric one-way ANOVA was used to compare these streamwise differences before, during and after construction.

Concentration and discharge data for LTC were used to generate estimates of annual loads of solids and nutrients by water year using the procedure developed by Runkel et al. (2004). Loads were also computed for wet (November–June) and dry (July–October) portions of each year. Discharge data were not available for TTC, so no load estimates were made for that watershed. LTC loads were based on the time series of streamflow for water years 2000–2004, sampled at regular 3 h intervals. Regression formulas for concentration as a function of discharge were calibrated using the available data and the method of adjusted maximum likelihood estimation. Only formulas with fits of acceptable quality (Runkel et al., 2004) were used to estimate loads. Estimated loads were divided

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by watershed area to compute yields for comparison with reports of workers studying other sites.

4. Results

4.1. Hydrology

Precipitation patterns for the two watersheds were similar, and average annual total precipitation during 1999–2005 was 1400 mm for both. Winter and spring were relatively wet (140 mm per month, November–June), and summer and fall were drier (80 mm per month July–October). LTC experienced severe drought in July–October 2000 (18 mm per month) and a wet period in April–June 2003 (213 mm per month). TTC experienced similar conditions with monthly averages of 46 mm for July–October 2000 and 156 mm for April–June 2003, respectively.

LTC peak discharges lasted only a few hours, with brief rise times and sharp peaks. Median rise and fall rates computed from mean daily stages were 6.4 and 1.6 times greater for the incised LTC than for the nonincised TTC. The range of stages observed at LTC concurrent with water quality sampling was 2.55 m over the period of record (1999–2005), while the ranges observed at TTC were 1.65 m at the upstream site and only 0.52 m at the downstream site for its period of record (1991–2003). The Richards–Baker flashiness index for LTC mean daily discharge during four complete years of the study ranged from 0.87 to 1.35. The contrasting hydrology for the two study reaches is highlighted when the medians of annual extreme stages are compared (Fig. 2). Median annual stages of all durations were less for LTC than TTC except for the one day maximum stage, which was 27% greater for LTC. In other words, TTC had deeper, more stable baseflows and high flows of longer duration with slower rise and fall times.

4.2. Water quality trends and seasonality

Trend tests of stage-adjusted TTC water quality data for 1991–2003 revealed only a slight downward trend in water temperature, indicating that the 1991–1995 fish collections reported by Shields et al. (2006) were obtained under water quality conditions similar to those studied here for 1999–2003. No temporal trends were detected for any parameter at LTC. During construction, median NO_3^- concentrations were about 0.03 mg L^{-1} higher at the LTC downstream site than before construction but were about 0.02 mg L^{-1} lower afterward ($p = 0.012$). However, no other water quality constituent exhibited a significant construction impact.

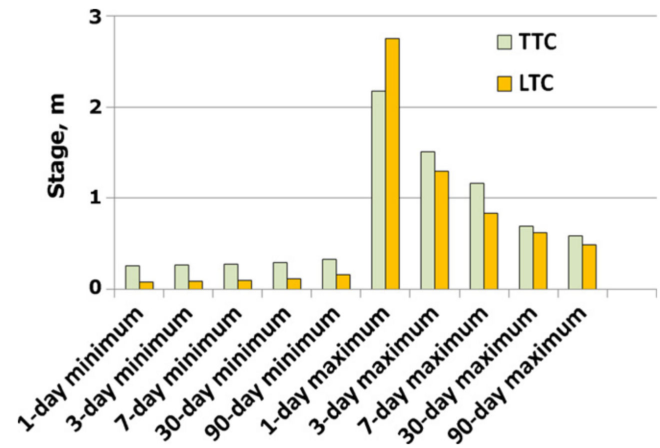

Fig. 2. Median values for stages with given annual duration for Little Topashaw (LTC, impacted by channel incision) and Toby Tubby Creeks (TTC, impacted by urbanization) in northern Mississippi. For comparibility, stage series for both streams were linearly transformed so that the mininmum observed stage = 0.0 m. Stage values for given durations were computed from these adjusted data using procedures provided by Richter et al. (1998).

Monthly summary statistics revealed a few seasonal patterns that echoed the hydrologic regime (Fig. 3a and b). During the wetter February–June period, both streams had higher levels of TS at their downstream sites than at their upstream sites. Turbidity levels exhibited patterns similar to TS, but dissolved solids did not. TTC hardness levels rose during the drier late summer and early fall months, while LTC hardness values were much higher during May and June, possibly reflecting periods of higher groundwater inflows for each stream. LTC alkalinity levels were elevated by about a factor of two during the drier months of May through November. Total and filterable P failed to exhibit seasonal patterns. Monthly median nitrate concentrations were positively correlated with monthly median discharge at LTC downstream ($r = 0.52$, $p = 0.087$). At TTC, elevated NO_3^- and NH_3 extremes occurred at the upstream site during Fall, when polluted urban contributions would have been less diluted. Both streams exhibited declining mean NO_3^- concentrations in late winter and increases in late spring and summer. Monthly median total P and TS were correlated at the TTC sites ($r > 0.6$), and monthly median ammonia and total N were correlated at LTC downstream.

Table 3
Spearman rank order correlation coefficients between selected water quality variables, measured hourly at downstream end of LTC study reach, with discharge for high flow (>1 m^3/s) conditions.

Water quality variable	Spearman *r*	Significance, *p*	No. of values
Hardness	−0.29	<0.001	503
Alkalinity	0.05	0.24	476
Turbidity	0.43	<0.001	815
Total solids	0.50	<0.001	806
Dissolved solids	−0.28	<0.001	809
Total P	0.54	<0.001	708
Filterable P	−0.05	0.38	362
NH_3	0.37	<0.001	861
NO_3^-	0.12	<0.001	850
NO_2^-	−0.15	<0.001	813
Total Kjeldahl N	0.26	<0.001	579
Total N	0.27	<0.001	755
Chlorophyll a	0.05	0.185	858
Fecal coliform	−0.15	0.0023	440
Enterococci	0.37	<0.001	437

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4.3. LTC storm flows and annual loads and yields

Examination of storm hydrographs and concurrent hourly water quality values for LTC revealed an almost random relationship between discharge and concentrations of most constituents. Some storm events displayed correlations between concentration and flow, while others did not. No patterns related to event magnitude, related constituents, or season were evident. Correlation coefficients between hourly values of discharge and water quality variables when discharges >1 m^3/s are shown in Table 3. Although rank order correlation coefficients were all <0.55, most correlations were highly significant ($p \leq 0.005$). Turbidity, TS, total P, enterococci and all species of N except NO_2^- increased with increasing flow; while hardness, dissolved solids, NO_2^- and fecal coliform decreased with increasing flow.

Loads and yields of total and dissolved solids, total N, total Kjeldahl N and total P were estimated, with results shown in Table 4, but regression models were not successfully fitted to data for stream-

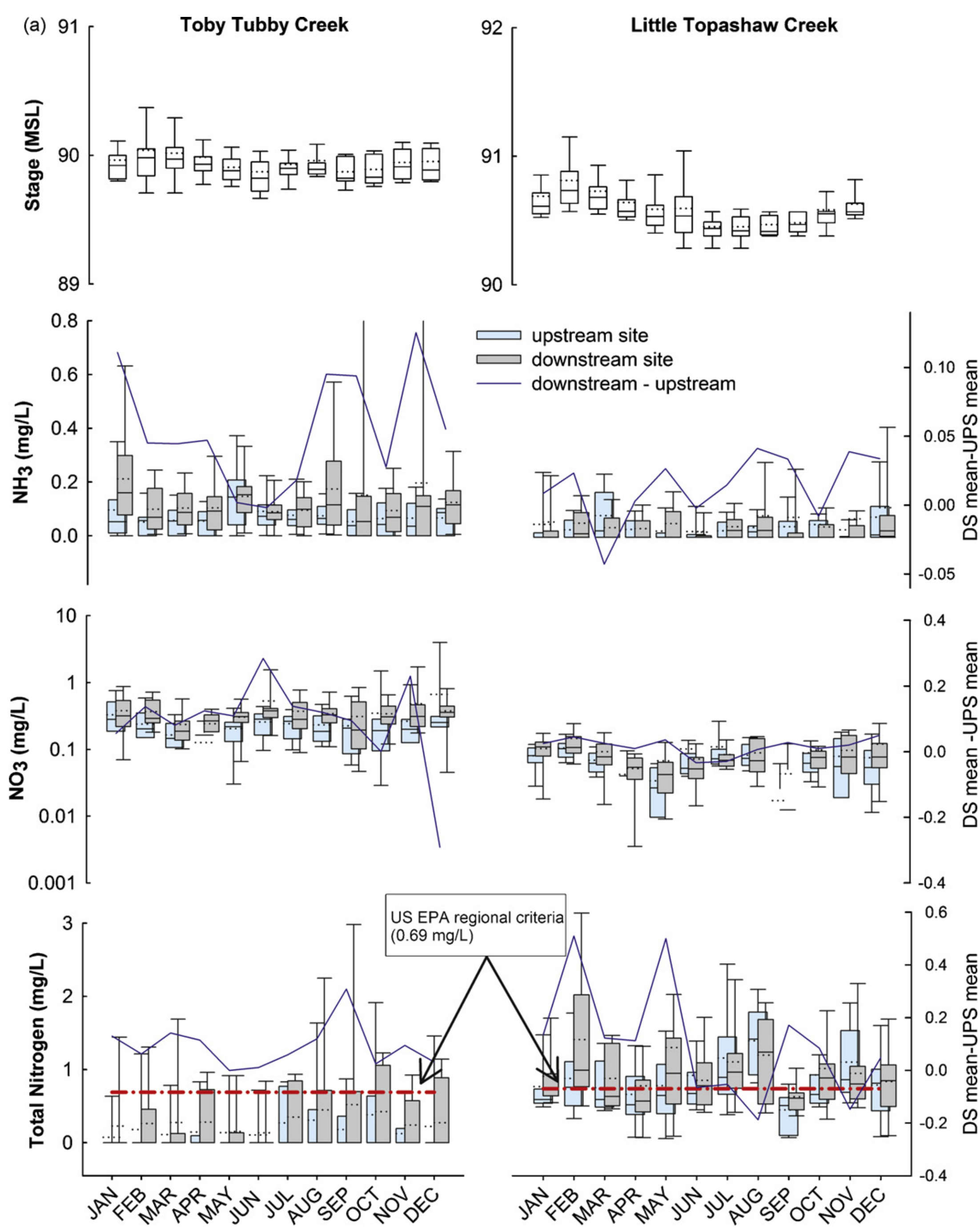

Fig. 3. (a) Box and whisker plots by month for stage, discharge, total solids, and total phosphorus for Little Topashaw (impacted by channel incision) and Toby Tubby Creeks (impacted by urbanization) in northern Mississippi 1999–2003. Top and bottom boundaries of boxes represent the 75th and 25th percentiles, respectively. Lines within boxes represent medians and means. Whiskers indicate the 90th and 10th percentiles, and symbols indicate outliers. (b) Box and whisker plots by month for stage, ammonia, nitrate, and total nitrogen for Little Topashaw (impacted by channel incision) and Toby Tubby Creeks (impacted by urbanization) in northern Mississippi 1999–2003. Top and bottom boundaries of boxes represent the 75th and 25th percentiles, respectively. Lines within boxes represent medians and means. Whiskers indicate the 90th and 10th percentiles, and symbols indicate outliers.

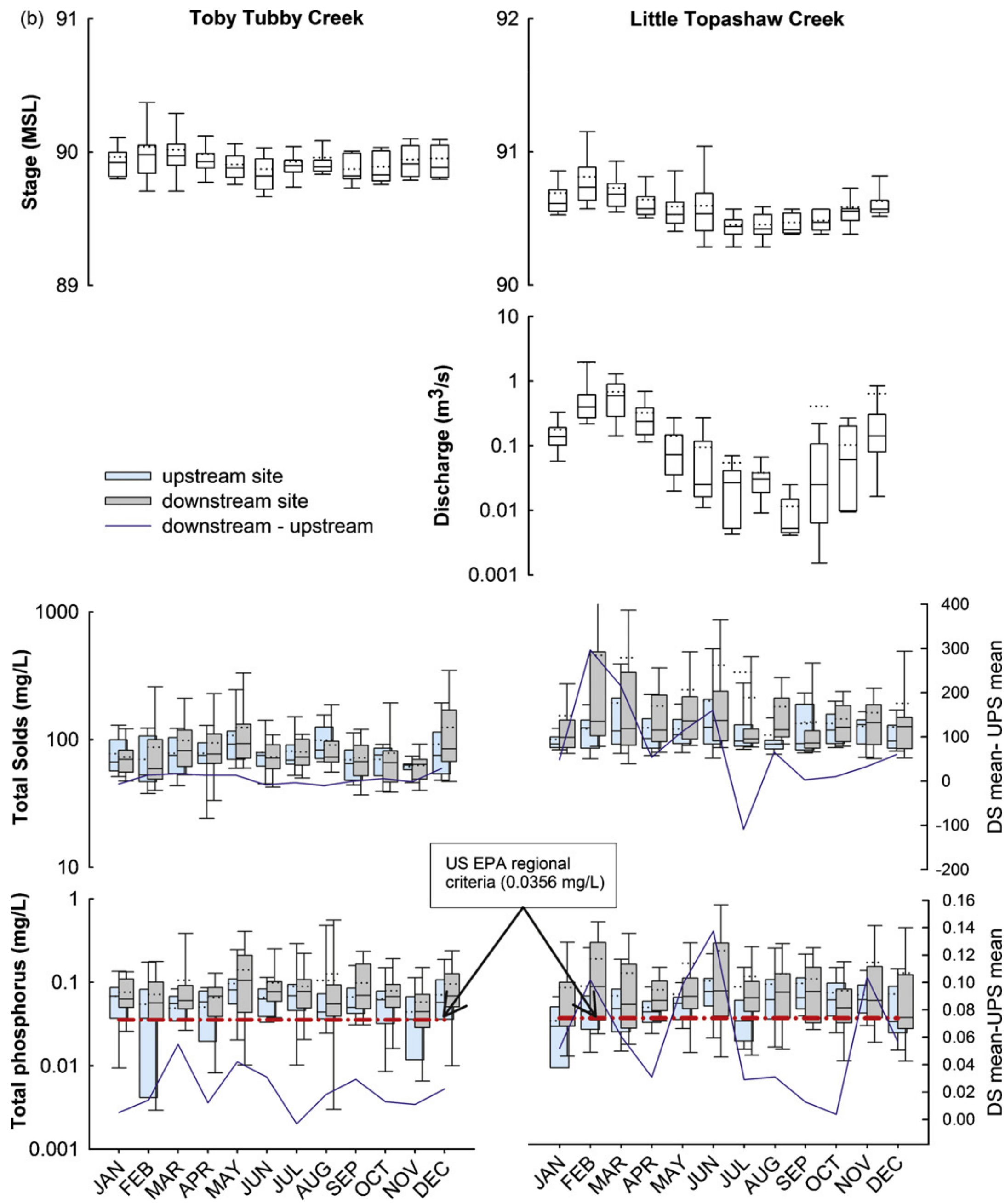

Fig. 3. (*Continued*).

Table 4
Estimated average yields and loads of solids and nutrients from the LTC study reach for water years 2000–2004.

Water year	Average annual yield, kg/ha/year				
	TS	DS	Total P	Total Kjeldahl N	Total N
2000	1859	164.9	1.52	2.24	2.65
2001	5946	360.9	5.17	5.16	6.18
2002	8643	353.5	7.97	5.22	6.38
2003	5252	356.5	4.54	4.98	5.93
2004	2689	231.2	2.23	3.14	3.72
Mean	4878	293	4.28	4.15	4.98
Standard error of prediction for mean yield	19.2	21	3.40	0.55	0.88
Mean load for dry season, kg/day	19	0.81	0.018	0.011	0.014
Mean load for wet season, kg/day	53	3.48	0.046	0.049	0.058
Total wet load/total load	2.8	4.3	2.6	4.3	4.1
Regression R^2	90%	97%	82%	90%	79%

Table 5
Summary statistics for all water quality data collected from Little Topashaw (impacted by channel incision) and Toby Tubby Creeks (impacted by urbanization) in northern Mississippi 1999–2003. Data from upstream and downstream sites were pooled for this summary.

Constituent	Little Topashaw Creek				Toby Tubby Creek				Ratio of medians, LTC/TTC
	Number	Median	Mean	Standard deviation	Number	Median	Mean	Standard deviation	
Physical									
Stage, m	626	0.16	0.20[a]	0.19	103	0.18	0.20	0.19	0.89
Temperature, °C	37,428	18.3	18.1	8.2	93	17.4	16.0	5.7	1.05
Conductivity, μmhos cm^{-1}	37,427	62	71	45	91	50	49	12	1.24
Dissolved oxygen, mg L^{-1}	36,007	9.5	9.7	2.6	93	8.2	8.3	1.6	1.16
Turbidity, NTU	664	25	79	215	77	19	35	47	1.32
Basic chemical									
pH	103	6.7	6.7	0.6	89	6.8	6.7	0.7	0.99
Hardness, mg L^{-1} as $CaCO_3$	552	40	42	21	70	30	27	12	1.33
Alkalinity, mg L^{-1} as $CaCO_3$	558	10	12	9	70	12	13	9	0.83
Sediment and solids									
Dissolved solids, mg L^{-1}	827	73	76	24	99	52	53	17	1.40
Total solids, mg L^{-1}	824	108	197	390	101	72	79	37	1.50
Phosphorus									
Filterable phosphorus, mg L^{-1}	792	0.013	0.007	0.038	98	0.010	0.015	0.020	1.30
Total phosphorus, mg L^{-1}	780	0.054	0.114	0.198	94	0.050	0.066	0.057	1.08
Nitrogen									
Ammonia, mg L^{-1}	831	0.000	0.052	0.123	103	0.025	0.085	0.151	0.00
Nitrite, mg L^{-1}	599	0.015	0.068	0.010	68	0.012	0.018	0.025	1.25
Nitrate, mg L^{-1}	836	0.067	0.085	0.104	103	0.297	0.326	0.197	0.23
Total Kjeldahl nitrogen, mg L^{-1}	615	0.637	0.862	0.763	72	0.525	0.656	0.476	1.21
Total nitrogen, mg L^{-1}	657	0.710	0.888	0.801	79	0.847	0.929	0.559	0.84
Biological									
Chlorophyll a, μg L^{-1}	825	4.09	8.90	29.97	101	4.17	6.63	11.04	0.98
Fecal coliforms, colonies/100 mL	642	0.	650	2300	97	270	2000	5100	0.00
Enterococci, colonies/100 mL	586	100	470	1400	90	500	1000	1300	0.20

[a] Stage statistics are for upstream sites on both streams. For ease of comparison, stage data for both streams were set so that their mean stage = 0.2 m.

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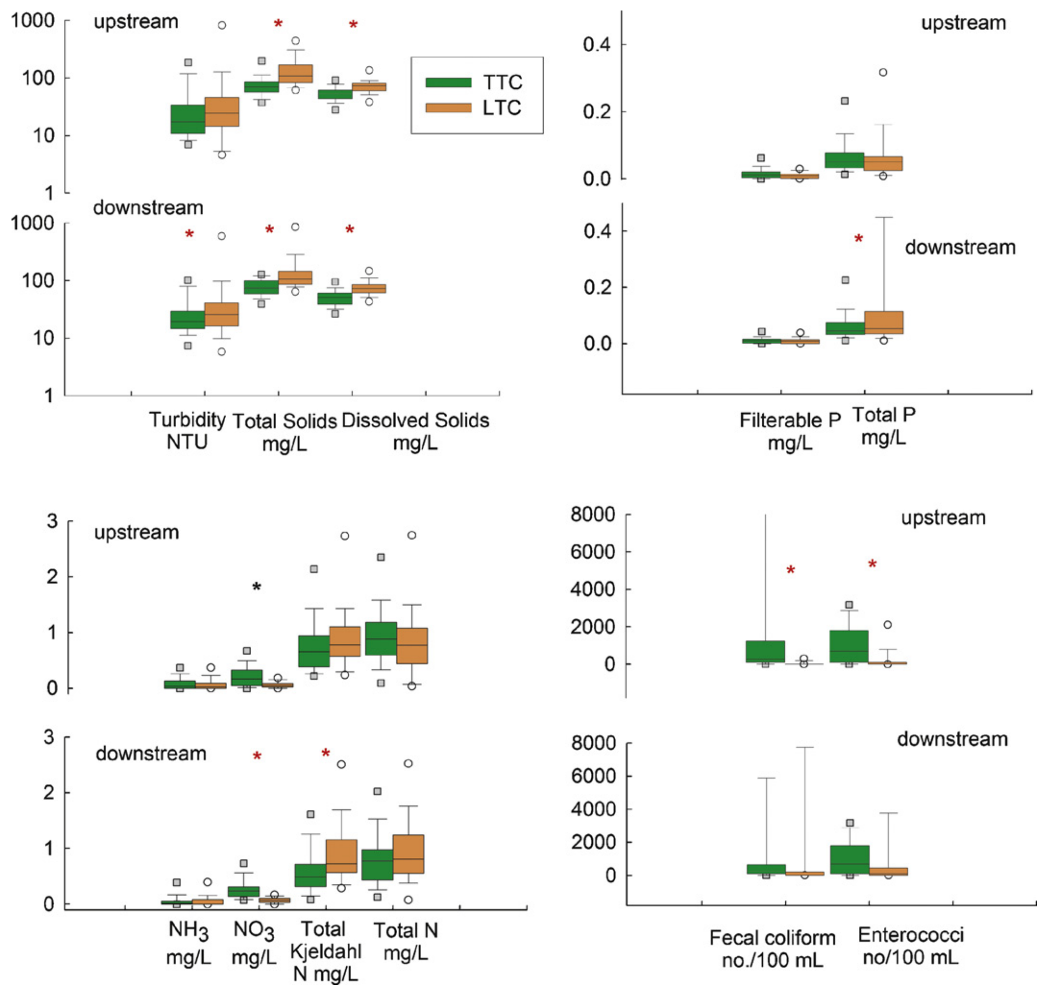

Fig. 4. Distributions of monthly measurements of selected water quality constituents at the upstream and downstream ends of the TTC and LTC study reaches, 1999–2003. Asterisks indicate significantly different distributions between the two streams (nonparametric ANOVA, $p < 0.02$).

flow and concentrations of filterable P, NH_3, NO_2^-, and NO_3^-, so no load estimates were made for those constituents. For all modeled constituents, estimated average yield magnitudes were closely associated with streamflow, and mean daily loads during wet season months (November–June) were 2.6–4.3 times as great as for dry season months (July–October). Over water years 2000 through 2004, about 90% of the total load of solids and nutrients exiting the LTC study reach did so during wet season months.

4.4. Comparison of streams

Comparison of the overall distributions of water quality characteristics reveals differences between the two streams (Table 5 and Fig. 4). Comparison data for each stream for the period 1999–2003 shows that mean turbidity and TS levels in LTC were two to three times higher than in TTC, while means of NO_3^-, NH_3, fecal coliform and enterococci bacteria were two to three times higher in TTC (Table 3). Both streams were slightly acidic (pH ~ 6.8) with low values of conductivity, hardness and alkalinity and similar levels of total and filterable P and chlorophyll a. LTC tended to be slightly warmer and have slightly higher levels of dissolved oxygen. The two streams displayed similar distributions of stage, pH, hardness, alkalinity, filterable P, NH_3, NO_2^-, total N and bacteria (nonparametric ANOVA of monthly data). Conductivity, dissolved oxygen, turbidity, TS, DS, total phosphorus (TP), total Kjeldahl N and chlorophyll a were all significantly greater at LTC, while NO_3^- was significantly greater at TTC ($p \leq 0.02$). Water quality differences between the upstream and downstream TTC sites were insignificant for most parameters, but levels of NO_3^- and total N were higher ($p < 0.04$) at the upstream site, and DO was about 1 mg L^{-1} lower at the downstream site ($p < 0.001$). At LTC, turbidity, TS, specific conductivity, TP, NO_3^-, chlorophyll a, fecal coliform and enterococci were all greater at the downstream site ($p \leq 0.016$).

5. Discussion

Most published research on channel incision focuses on erosion or sedimentation processes, their causes, or their impacts. A complete understanding of channel incision should encompass the full range of impacts that constitute this syndrome: geomorphic instability, altered hydrology, degraded water quality, and biological effects. Both LTC and TTC are part of a landscape dramatically impacted by anthropogenic influences over the last two centuries. However, only the LTC study reach exhibited typical incision symptoms: it was rapidly eroding and was about twice as deep and four times as wide as LTC, with less instream wood and riparian vegetation (Fig. 1 and Table 1). Incision of LTC was associated with perturbed hydrology relative to TTC and other nonincised sites. The difference in flow between LTC and TTC is highlighted by Fig. 2 which shows that the annual maximum stage for LTC was about 17 times the annual 90-day minimum while a similar ratio for TTC was about 7. The Richards–Baker flashiness index for LTC (0.87–1.35)

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was considerably higher than values for similar-sized streams in the Midwestern U.S. (0.05–1.05, Baker et al., 2004). The range for Midwestern streams was based on 27-year means for 42 sites with contributing drainage areas between 34 and 81 km^2. Other workers have noted the tendency of channels enlarged by incision to experience high flows that peak higher and faster as more water is contained within the channel (Happ et al., 1940; Knox, 1987; Shields and Cooper, 1994; Faulkner and McIntyre, 1996; Doyle and Shields, 1998; Bledsoe and Watson, 2001; Schilling et al., 2004).

Cooler temperatures at TTC likely reflected heavier riparian shading than for LTC, which may also have mediated water quality processes related to photosynthesis (Ghermandi et al., 2009). As noted above, dissolved oxygen and chlorophyll a were higher and NO_3^- levels were lower in the less-shaded LTC. Total solids concentrations at LTC were more than double those at TTC and were associated with flashy hydrology and channel erosion. Solids concentrations may have been the most important difference in water quality between the two streams (Cooper and Knight, 1991; Newcombe and Jensen, 1996; Sutherland et al., 2002), and actual suspended sediment differences were likely even greater than TS differences. The TS concentrations reported here were based on analysis of aliquots of shaken grab samples collected either by automated pumping samplers or by manually dipping open containers into the center of the stream. Since our samples were collected at a single point within a cross-section and were not integrated, TS concentrations likely varied widely and were biased low relative to the flow-weighted mean (Kuhnle and Wren, 2006; Gray et al., 2000). The estimated average annual TS yield for LTC was about half as great as the average of suspended sediment yields from incised streams in northwestern Mississippi reported by Shields et al. (1995). Simon and Klimetz (2008) showed that the median of mean annual suspended sediment yields from unstable channels such as LTC was about three times higher than yields from stable "reference" sites such as TTC in the ecoregion that contains these two watersheds.

Others have noted the linkages between flashy hydrology and elevated levels of nutrients in streams (Pionke et al., 2000; Norton and Fisher, 2000). Measured total N and total P were frequently in excess of regional criteria promulgated by the USEPA (undated, 2000) as shown by Table 3 and Fig. 4. In fact, EPA nutrient criteria for streams in the U.S. are rarely met, and LTC and TTC median concentrations were generally lower than those reported for similar sized-watersheds in the region (Shields et al., 2009c). Furthermore, mean total N concentrations for these streams were lower than for 92% of 111 agricultural watersheds across the U.S. (Mueller and Spahr, 2005). Mean total P concentrations were lower than those computed for about 80% of these watersheds. Estimated total N yields for LTC were low relative to those presented by Domagalski et al. (2008) for five agricultural watersheds spanning a wide range of climatic and geohydrologic conditions across the U.S. Conversely, total P yields were relatively high. Of the five, the watershed most similar to LTC was Morgan Creek, MD, a 31 km^2 watershed supporting cultivation of corn and soybeans on fine silt loam soils (Capel et al., 2008). Estimated mean annual yields of total N and total P from Morgan Creek were 17 kg/ha and 1.3 kg/ha, respectively. LTC estimated yields were more than three times lower for total N and more than three times higher for total P (Table 5). On a national basis, estimated LTC N yields were lower than those computed for about 75% of the agricultural and mixed-cover watersheds studied by Mueller and Spahr (2006), but P yields were in the top 10%, which may reflect the rather large standard error for the P estimate (Table 5).

Longitudinal differences in chemical water quality may reflect land use along the study reaches. In general, water quality improved in the streamwise direction along the TTC reach and declined along the LTC reach. The zone of forest and wetlands between the developed areas of the TTC watershed and the study reach (Fig. 1) provided a protective buffer that LTC did not enjoy; most of the cultivated lands in the LTC watershed bordered the study reach even though this land use comprised only 7% of the total watershed. Furthermore, steep, eroding banks 4–7 m high and riparian gullies were common along the channel between the two LTC sites, and the channel was flanked by fields planted in corn, cotton, or soybeans interspersed by small patches of woods. No fewer than 26 ditches and gullies conveyed concentrated runoff from these fields into the channel along the 2 km reach between the sampling sites. In contrast, NO_3^- and total N concentrations were reduced as water moved through the TTC study reach, which was flanked by wetlands and beaver pond complexes. Total P concentration in small Pennsylvania streams was more closely related to the presence of high-P soils within 60 m of the stream than their presence throughout the contributing watershed (Sharpley et al., 1999). Riparian buffer zones may mitigate impacts of high sediment loads on fish (Rabeni and Smale, 1995), and riparian land use has been found to exert a strong influence on sediment and P inputs to streams in Iowa (Zaimes et al., 2008). Local conditions are more important than basin-scale land use in determining physical characteristics of streams (Stauffer et al., 2000; Goldstein et al., 2007).

Other workers have attempted to define stream water quality criteria for ecological impairment. Maul et al. (2004) reported results of sampling benthic macroinvertebrates, physical habitat, and water quality from 44 stream reaches including TTC in northern Mississippi. Ordination analyses based on macroinvertebrate collections showed that concentrations of NH_3, TP, TS and conductivity were important determinants of macroinvertebrate community composition. Interestingly, all of these variables except for NH_3 differed significantly between LTC and TTC (Fig. 4). The severity of channel incision and attendant physical habitat degradation was not a good predictor of macroinvertebrate community structure, but "least disturbed" sites could be distinguished using ordination analysis. Comparison of instream concentrations of total N and total P in 29 Pennsylvania watersheds indicated a wide gap or "threshold" between 12 biologically impaired and 17 unimpaired watersheds (Sheeder and Evans, 2004). Impairment thresholds, which were calculated from the distributions of average concentrations, were estimated to be 2.01 $mg\,L^{-1}$, 0.07 $mg\,L^{-1}$, and 197.27 $mg\,L^{-1}$ for N, total P and suspended sediment, respectively. Based on these criteria, TTC would have been borderline with respect to P, and LTC would have been impaired due to elevated P and suspended sediment (assuming suspended sediment $\geq$ TS, as noted above). In both streams, average total N concentrations were less than half the Pennsylvania threshold. Removing land from cultivation in a German watershed produced reductions in N and P over a four-year period in a first-order stream. Average dissolved inorganic N concentration was reduced from 10.4 $mg\,L^{-1}$ to 0.9 $mg\,L^{-1}$, and average soluble reactive P from 0.13 $mg\,L^{-1}$ to 0.09 $mg\,L^{-1}$. These water quality changes were associated with shifts in benthic invertebrate community structure from a chironomid–amphipod assemblage to an oligochaete–gastropod dominated community (Chambers et al., 2006). Studies in small channelized streams (drainage ditches) in Midwestern agricultural watersheds found that fish communities exhibited weak but significant negative correlations with NH_3 and NO_3^- (Smiley et al., 2009), while instream habitat had a greater influence (Smiley et al., 2008). Workers in other Midwestern agricultural watersheds failed to detect water quality impacts on fish (Fitzpatrick et al., 2001; D'Ambrosio et al., 2009); however, the NH_3 and NO_3^- levels that they observed were lower than levels reported by Smiley et al. (2009). LTC and TTC also had much lower levels of nitrate

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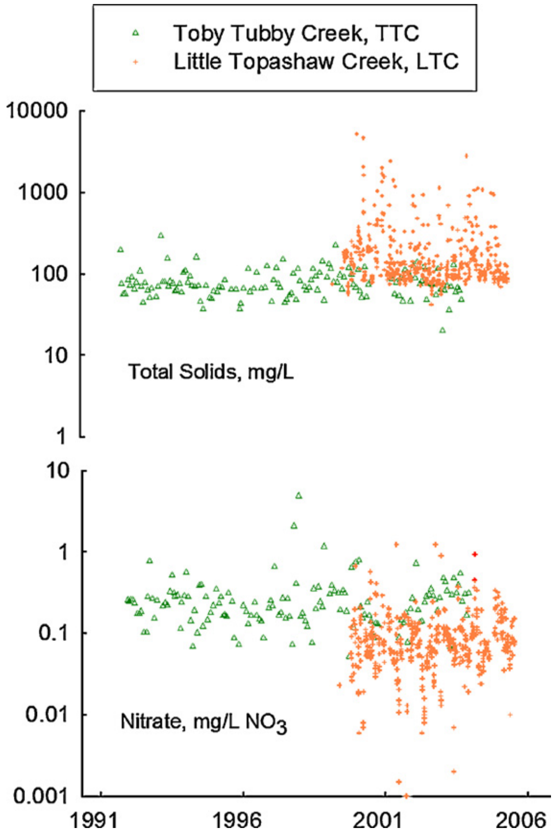

Fig. 5. Time series plots showing periods of record for two selected water quality constituents for Toby Tubby and Little Topashaw Creeks, Mississippi. As discussed in text, statistical trend detection tests showed data were free of temporal trends.

and ammonia than the drainage ditches sampled by Smiley et al. (2008): they found a maximum NH_3 concentration of 3.05 mg L^{-1} and a maximum $NO_2^- + NO_3^-$ concentration of 20.92 mg L^{-1}, while our maxima were 1.66 mg L^{-1} NH_3 and 2.60 mg L^{-1} $NO_2^- + NO_3^-$.

Although TTC fish collections were not contemporaneous with the 1999–2003 period for which we compare LTC and TTC water quality, the absence of trend in TTC water quality (Fig. 5) indicates that the TTC fish collections were representative of chemical water quality conditions similar to those for 1999–2003. Biological quality of TTC, as indicated by fish, was clearly superior to LTC. TTC was far more speciose than LTC (Table 2), and the differences in species composition and relative abundance were even more striking. The differences in fish collections from LTC and TTC are clearly linked to incision-related differences in hydrology (Shields et al., 1994; Shields and Cooper, 1994; Doyle and Shields, 1998; Konrad and Booth, 2005) and physical habitat (Holtrop and Fischer, 2002; Shields et al., 2006), but the differences in water quality described here may also have contributed synergistically to biotic degradation.

6. Conclusions

Warmwater streams in the southeastern U.S. represent ecological resources and reservoirs of biological diversity that are rapidly diminishing due to anthropogenic influences. Channel incision is particularly pernicious, as it results in degradation of both physical habitat and water quality and is linked to perturbed hydrology. In this study we compared water quality conditions in a severely incised, rural channel with those in a nonincised stream with a partially urbanized watershed. Although the urbanizing stream had higher levels of N and bacteria, it supported almost twice as many fish species in an assemblage typical of more stable, less degraded systems (Shields et al., 1998). Perhaps this was because the stream was protected by a buffer of floodplain wetlands and because watershed and stream management had not triggered channel incision and associated hydrologic perturbations. The incised stream with inferior fish fauna was characterized by much higher sediment concentrations and turbidity, degraded physical habitat and flashy hydrology. We conclude that channel incision presents a syndrome that is characterized by perturbed hydrology, degraded physical habitat, elevated nonpoint source pollution, and depleted fish species richness and that is extremely deleterious to instream ecosystem services.

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