Response of Fishes and Aquatic Habitats to Sand-bed Stream Restoration Using Large Woody Debris

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Abstract

Pre- and post construction data are presented that describe effects of habitat rehabilitation of Little Topashaw Creek, a sinuous, fourth-order sand-bed stream draining 37 km^2 in northwest Mississippi. The rehabilitation project, constructed in 2000, consisted of placing 72 large woody debris structures along eroding concave banks and planting 4000 willow cuttings in sandbars. Response was measured by monitoring flow, channel geometry, physical aquatic habitat, and fish populations. Initially, debris structures reduced high flow velocities at concave bank toes, preventing further erosion and inducing deposition. Physical response during the first year following construction included creation of sand berms along eroding banks and slight increases in base flow water width and depth. Fish collections showed assemblages typical of incising streams within the region, but minor initial responses to debris addition were evident. Progressive failure of the structures and renewed erosion were observed during the second year after construction.

Introduction

Warmwater streams in the Southeastern U.S. have remarkably high levels of biodiversity and are thus important ecological resources. However, many of these streams are severely degraded by erosion and sedimentation linked to human activities. Channel incision, typified by headward-progressing channel erosion in the upper parts of watersheds and attendant downstream sedimentation, is endemic across much of the region. Annual sediment yield is ~1000 t km^{-2}, or about an order of magnitude more than the national average (Shields et al., 1995). Physical aquatic habitat quality is poor in incised reaches, usually exhibiting a surplus of shallow water depths and shifting, sandy substrate and a deficit of woody debris, pool habitats, and stable substrates (Shields et al., 1994).

In incising channels, large woody debris (LWD) is input to channels by bank failure processes, and in-channel debris accumulations are associated with sediment retention (Potts & Anderson, 1990; Downs & Simon, 2001), in some cases reversing incision (Shields et al., 2000). LWD is an important component of aquatic habitat in warmwater streams, retaining particulate organic matter (Bilby & Likens, 1980), providing substrate for biomass production by benthic macroinvertebrates (Benke et al., 1985), and fostering higher levels of invertebrate species richness and abundance (Cooper & Testa, 1999). Debris formations create zones of flow acceleration and deceleration that provide higher levels of physical diversity (Shields & Smith, 1992), which are important to fish (Angermeier & Karr, 1984; Warren et al., 2002). Native species are likely adapted to high debris densities typical of North American streams prior to European settlement when debris was abundant due to beaver (*Castor canadensis*) activity and the absence of human actions to remove debris and old-growth forests (Triska, 1984). We hypothesized that recovery of physical aquatic habitat and fish community structure could be accelerated by placing LWD structures in an incised, warmwater stream.

Study site

A study site was selected along 2 km of Little Topashaw Creek, a fourth-order stream (1:24,000 topographic map) in north central Mississippi draining about 37 km^2 (Figure 1). Criteria used in site selection included rapid bank erosion, an abundant supply of sandy bed material from upstream, nearby sources of native plant and animal colonists, and an advanced stage of incised channel evolution (Simon & Darby, 1999). The single-thread, meandering channel had an average sinuosity of 2.1, an average slope of 0.002, an average width of 35 m, and an average depth of 6 m. Channel bed materials were primarily 0.2 to 0.3 mm sand. Channel morphology was extremely dynamic, typical of incising channels in the region. Historical air photos suggest mean channel width increased by a factor of 4 to 5 between 1955 and 1997. Surveys of 13 cross sections before and after a flow of 55 $m^3 s^{-1}$ (peak stages reached mid-bank elevation) that occurred three months prior to our addition of LWD indicated an average increase in cross-sectional area of 10% (std dev = 8%) with bank retreat as great as 7.6 m (mean = 2.0 $\pm$ 2.6 m). This event triggered 60 m of upstream migration of a 0.6-m high headcut and produced two chute cutoffs across point bars.

Addition of large woody debris

Large woody debris structures were designed as described by Shields et al. (In press, 2001) and constructed on concave, eroding banks using either woody debris (~10%) or living trees (~90%). Living trees were $\geq$ 0.20 m diameter at breast height, an average of 6.7 $\pm$ 3.2 m long, and were harvested with root balls and crowns intact. The finished project consisted of 72 structures built with 1,168 trees obtained by clearing 3.4 ha. Placement of structures produced an order of magnitude increase in woody debris loading within the project reach (Figure 1b). Logs placed perpendicular to the flow direction ("key members") were ~9 m long and were partially buried in trenches excavated into banks when bank slopes were gradual enough to permit trench excavation. About 52% of the logs used had intact rootwads, and about 30% of the rootwads retained a ball of soil. To provide additional structural stability during high flows, metal earth anchors were cabled to 58 (80%) of the completed structures. About 4,000 willow (*Salix nigra*) cuttings were planted on point bars and in sediment deposits adjacent to selected debris structures using a water-jetting technique. Including willow planting, costs for construction were approximately US$88 m^{-1} channel treated, roughly 20% to 50% of costs for recent construction of traditional stone stabilization projects in the region.

Methods

Effects of debris addition on physical habitat quality and fish were quantified by semiannual (June and late September or early October) sampling of selected subreaches at base flow during 1999-2001 inclusive. Although debris structures were constructed during July-August 2000 and willows were planted during January-February 2001, the 1999-2000 data were classified as “before debris addition,” and the 2001 data, “after debris addition.” The October 2000 data were influenced only minimally by the debris structures because a prolonged drought prevented the structures from exerting any effects on channel morphology until November 2000.

Five, 150-m-long subreaches were sampled: two were downstream of the modified region in a reach geomorphically similar to the treated reach, two were within the modified, and one was in a straight, relatively narrow channel immediately upstream. Within each reach, physical habitat variables were measured along 10 transects placed at 15-m intervals. Five to seven measuring points were located 25 cm from the left bank and at equal intervals along each transect. At each point, water depth was measured with a wading rod. Water surface width was measured with a metric tape measure at each transect, and visual observations regarding the presence and dimensions of woody debris formations and the type of bank vegetation were recorded. Discharge was computed using depth and velocity data collected at cross sections upstream from, within, and downstream from the modified reach using a wading rod and an electromagnetic current meter. Fish were sampled concurrently with physical habitat using a backpack-mounted electroshocker as described by Shields et al. (1998).

Effects of debris addition on flow patterns that contribute to retention of fine particulate organic matter were quantified using a tracer dye experiment 9 months after construction. Discharges during the dye experiment (~0.3 $m^3 s^{-1}$) were above base flow, but well below high flow levels. Slug-injections of Rhodamine WT dye were made upstream and downstream from the treated reach, and passage of the resulting dye cloud was documented by periodically collecting grab samples for several hours 1.3 to 1.7 km downstream from the injection points. The reach traversed by the downstream dye cloud had similar flow resistance characteristics (bed slope, channel cross section, bed material size, sinuosity) to the treated reach except for the presence of the debris structures and the attendant features created in the channel bed by scour and deposition adjacent to the structures. The downstream study was completed first to avoid interference from the upstream injection. Samples were returned to the laboratory and analyzed for dye concentration using a Turner 10-AU-005-CE fluorometer calibrated with a blank and a standard solution of 100 ppb at a temperature of 23^{o}C. Fluorometer readings were compensated for temperature differences between the sample and the standard. Time-concentration curves were normalized by dividing the time values by reach length

Effects of debris on aquatic habitats during high flows were observed using acoustic-Doppler depth-velocity loggers as described by Shields et al. (2001). Loggers were secured above the stream bed along a transect across the channel within a bend where debris structures had been placed on the concave bank and within an unmodified, eroding bend with similar geometry to the modified bend. Depth and velocity measurements were recorded every 5 min during major runoff events. Debris effects on erosion and deposition were quantified using cross-section and thalweg surveys conducted before and during the first year after construction as described by Shields et al. (In Press).

Results and Discussion

Physical habitat data collected at similar discharges before (Spring = 0.048 $m^3 s^{-1}$, Fall = 0.018 $m^3 s^{-1}$) and after (Spring = 0.043 $m^3 s^{-1}$, Fall = 0.012 $m^3 s^{-1}$) construction showed that scour adjacent to the woody debris structures and beaver dams resulted in deeper (~2x) and slightly wider aquatic habitats at baseflow relative to pre-construction conditions (Figure 2). Untreated reaches up- and downstream became shallower or were unchanged. Water depths were greater in the upstream reach than within the treated reach or downstream due to the presence of several upstream-migrating nickpoints. The upstream reach was typical of a transitional phase that is a precursor of the inferior conditions downstream (Shields et al., 1998). The treated reach became significantly deeper following debris addition ($p \leq 0.003$, Mann-Whitney Rank Sum Test) while Fall depths were shallower in comparison reaches ($p < 0.002$). Trends in water surface width were not as clear (Figure 2). Width decreased upstream and increased slightly downstream, but increased significantly in the treated reach ($p < 0.001$). Mean water width in the treated reach increased from 3.0 m in Fall 1999 (before addition of woody debris structures) to 5.0 m in the Fall of 2001.

The dye experiment showed that debris structures increased flow resistance, moderating velocities and increasing retention times (Figure 3). Mean velocity for the treated reach was 17 cm s^{-1}, but 29 cm s^{-1} for the downstream reach. Although the mean velocity was less in the reach treated with debris, dispersion was nearly the same for both reaches, as evidenced by the width of the dye curves in Figure 3.

Acoustic-Doppler loggers recorded velocities within debris structures that were only 50% to 60% as great as those in the channel adjacent to the structure or in the bend without debris structures

(Figure 4). Velocities within the debris structure were generally less than 30 cm s^{-1}, and usually below 10 cm s^{-1}, even during events that were large enough to produce flow depths > 3 m. Events with depths of only ~ 1m produced velocities > 100 cm s^{-1} in the bend without debris structures. Habitat preferences of centrarchids and ictalurids generally lie within the 10 to 50 cm s^{-1} range (e.g., Stuber et al., 1982, McMahon and Terrell 1982).

Changes in fish population density, average size, and community structure (Table 1) mirrored trends observed in other incised stream ecosystems (Shields et al., 1997 and 1998). Collections were dominated by cyprinids (90% of numbers, 64% of biomass) and centrarchids (6% of numbers, 27% of biomass), but the relative dominance of cyprinids was inversely related to the mean water depth ($r^2 = 0.30$, $p = 0.002$) (Figure 5). Opposite trends were indicated for numbers and biomass of the centrarchids with $r^2 = 0.59$ and 0.54, for the association between percent of numerical and biomass catch, respectively, and mean depth ($p < 0.00005$). Addition of pool habitat following debris addition increased the fraction of numbers and biomass comprised by centrarchids in the treated reach from 3% to 10% and from 13% to 23%, respectively. Species richness was unaffected by debris addition, but the average number of species per 150-m reach increased in all three zones (upstream, within the treated reach, and downstream) following debris addition (Table 1). Three species typically associated with deeper habitats were captured in the treated reach following debris addition but not before (*Micropterus salmoides*, *Lepomis megalotis*, *Ictalurus punctatus*), and *M. salmoides* was found only in the restored reach. Although changes in the size of centrarchids were not statistically significant ($p>0.16$, Mann-Whitney Rank Sum Test) in any of the zones, only one of the 27 centrarchids captured in the two years before debris addition was longer than 10 cm, but 4 of the 40 captured afterward were longer than 10 cm.

Stream bank erosion was initially checked by placement of the debris structures, and deposition of sand berms adjacent to steep, concave banks was conducive to stability during the first year following construction. However, many of these deposits were scoured away during high flows and attendant bed degradation occurring 16 and 17 months following construction, resulting in progressive failure (loss of woody materials) of ~30% of the structures and renewed erosion of banks.

Conclusions

Addition of LWD in the form of engineered structures produced marginal improvements in physical habitat quality in a rapidly incising sand bed stream. Fish community responses were more subtle, but were consistent with previous observations of response to addition of pool habitats in incising warmwater streams. Progressive failure of the structures leaves the prospects for long-term ecological recovery in doubt.

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Table 1. Summary of electrofishing catch, Little Topashaw Creek, Mississippi. Means followed by different letters are significantly different (p =0.05, Two-way ANOVA).

Quantity	Upstream Reach		Reach modified by debris addition and willow planting		Downstream Reach	
	Before construction	After Construction	Before construction	After Construction	Before construction	After Construction
Mean no. of fish per sample[1]	74 ± 79[a]	80 ± 20[a]	129 ±72[a]	132 ±106[a]	139 ± 75[a]	213 ± 150[a]
Mean biomass, g per sample	262 ± 155[a]	280 ± 110[a]	149 ± 78[a]	187 ± 74[a]	166 ± 95[a]	323 ± 208[a]
Total no. of species	12	12	18	16	16	16
Mean no. of species per sample	6.8 ± 0.8[a]	8.0 ± 1.4[a]	6.0 ± 2.7[a]	9.3± 2.2[b]	5.4 ± 2.8[a]	11.0 ±0.0[b]
Centrarchids, % of total catch by number	18	16	3	8	6	5
Largest fish (length, cm)	17	17	12	17	20	13

[1] The expression "sample" here refers to a collection from a 150-m long sampling reach.

List of Figure Captions

Figure 1. Reaches of Little Topashaw Creek, Mississippi sampled for this study.

a. Upstream.

b. Restored reach showing large woody debris structures on outside of bend one year after construction.

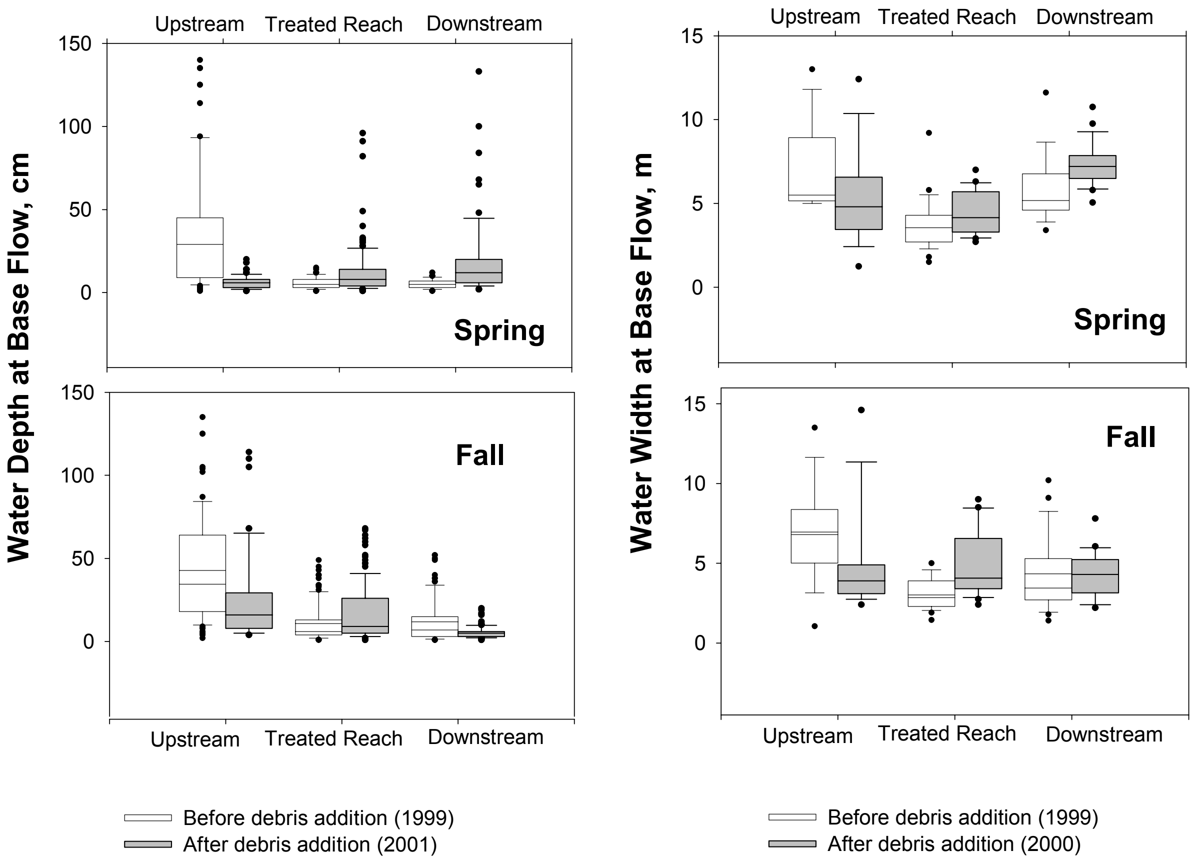
c. Downstream.

Figure 2. Distribution of water depth and width before and after addition of woody debris to restored reach in late summer 2000.

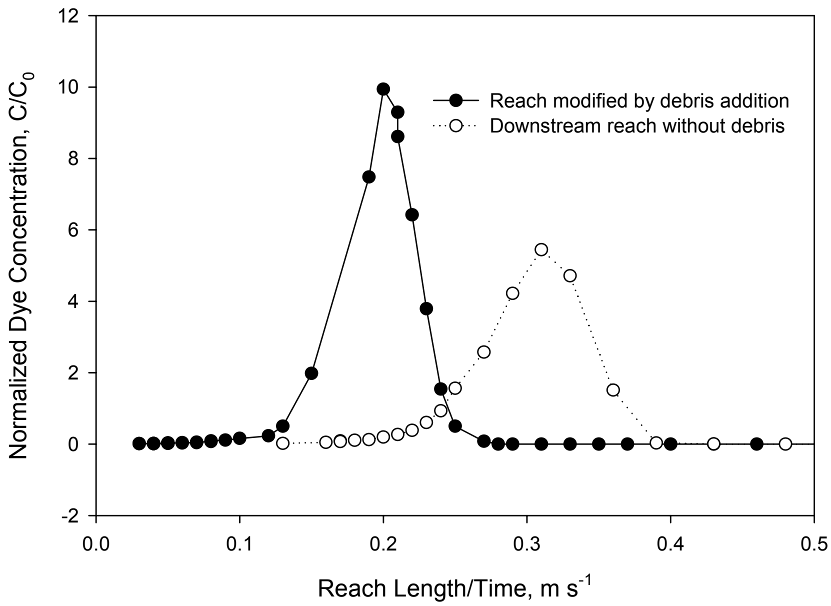
Figure 3. Tracer dye concentration curves following slug injection of fluorescent dye. X-axis represents reach length divided by time.

Figure 4. Effect of large woody debris structures on high flow velocities. Velocity measured by acoustic-doppler loggers is plotted on the x-axis against simultaneous records of flow depth plotted on the y-axis for locations within bends with (top) and without (bottom) debris structures along the outside of the bend.

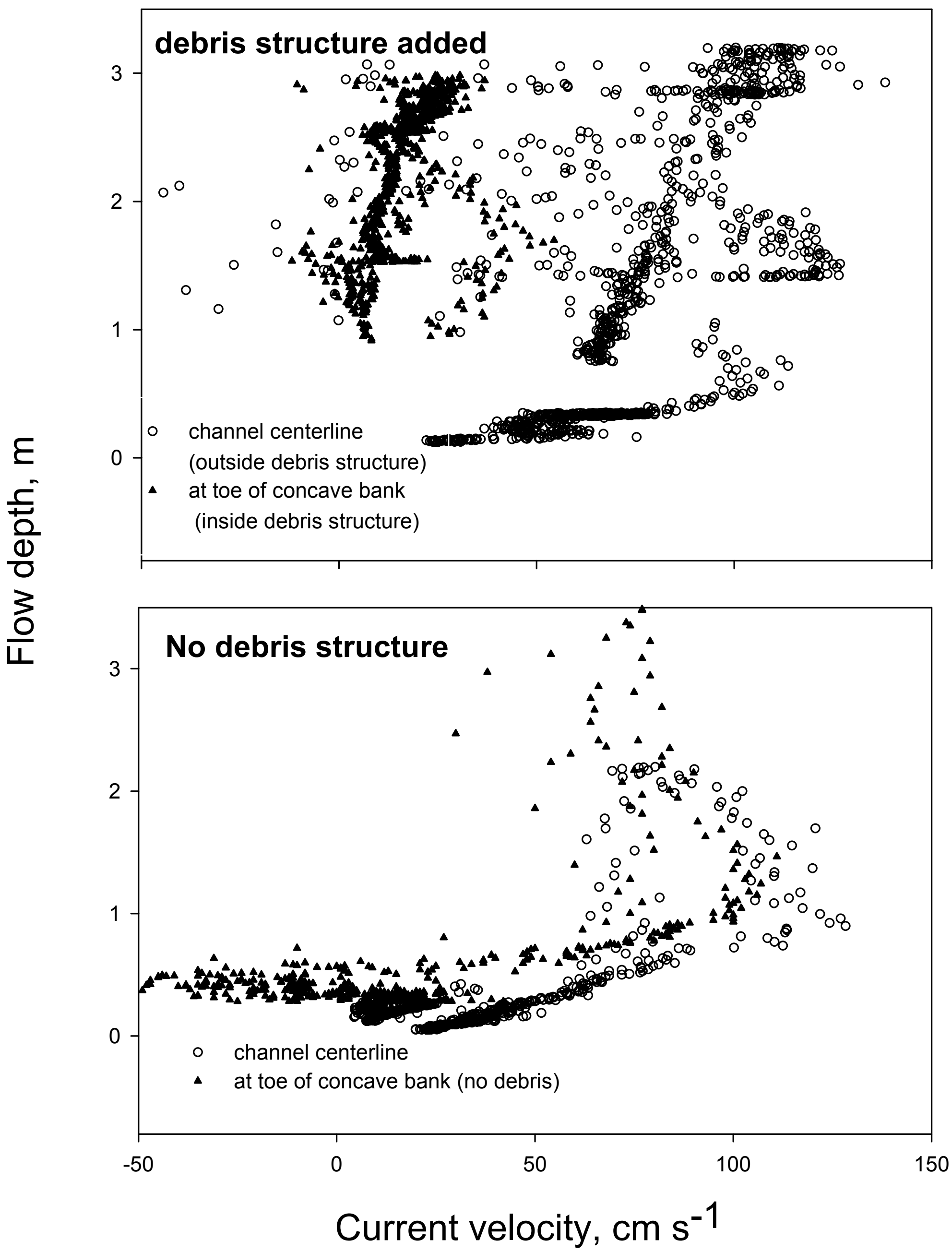
Figure 5. Response of cyprinids (white symbols) and centrarchids (black symbols) to changes in mean water depth. The upstream, restored, and downstream reaches are represented by circles, triangles, and squares, respectively.

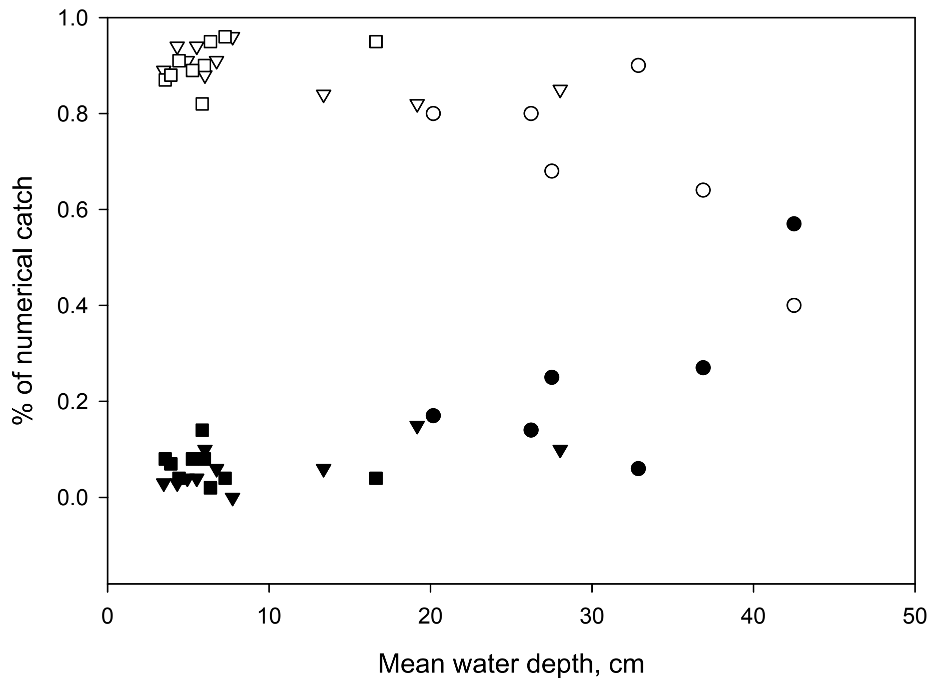


Upstream
Treated Reach
Downstream
Water Depth at Base Flow, cm
150
100
50
0
Spring
Fall
Before debris addition (1999)
After debris addition (2001)
Water Width at Base Flow, m
15
10
5
0
Spring
Fall
Before debris addition (1999)
After debris addition (2000)



Normalized Dye Concentration, C/C0
Reach Length/Time, m s-1
Reach modified by debris addition
Downstream reach without debris
12
10
8
6
4
2
0
-2
0.0
0.1
0.2
0.3
0.4
0.5


debris structure added
channel centerline
(outside debris structure)
at toe of concave bank
(inside debris structure)
No debris structure
channel centerline
at toe of concave bank (no debris)
Flow depth, m
Current velocity, cm s-1
3
2
1
0
-50
0
50
100
150


1.0
0.8
0.6
0.4
0.2
0.0
% of numerical catch
0
10
20
30
40
50
Mean water depth, cm