Effects of large woody debris removal on physical characteristics of a sand-bed river

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ABSTRACT

1. Removal of large woody debris (LWD) is one of the most widely practised stream alterations, particularly in sand-bed rivers of the south-eastern USA. Selective removal of LWD has been proposed as an alternative to orthodox non-selective clearing in order to conserve ecological resources, but methods for comparing hydraulic and environmental effects of selective and non-selective removal have not been developed. Conservation of stream habitats requires quantification of LWD removal impacts on physical habitat.

2. Physical characteristics of straightened, sand-bed reaches of the South Fork Obion River in western Tennessee, USA that were rich in LWD were compared with those in similar reaches where debris had recently been removed using selective removal guidelines.

3. The mean volume of LWD per unit water volume was 0.0545 in the uncleared reaches, but nearly 60% lower (0.0225) in the cleared reach.

4. A simple technique for predicting hydraulic roughness in channels with varying amounts of LWD was developed. Hydraulic roughness, as measured by the Darcy–Weisbach friction factor, was about 400% greater in uncleared reaches at base flow but declined to a level about 35% greater than for the cleared reaches at higher flows. Predicted friction factors were within 35% of measured friction factors at higher flows.

5. Physical habitat diversity in this channelized sand-bed stream was strongly related to the density of LWD. Flow conditions in the uncleared reaches were more heterogeneous than in the cleared reach, especially at low flow. At low flow, uncleared reaches tended to be shallower, have lower velocities, slightly finer bed material, and more heterogeneous conditions overall. Shannon indices based on depth and velocity were an average of 48% higher in uncleared reaches.

6. Bed sediments underneath and immediately adjacent to LWD formations were finer and contained more organic matter than sediments distant from LWD. However, when all bed samples were considered, organic content was positively correlated with median grain size.

INTRODUCTION

Large woody debris (LWD) has been the subject of increasing scientific interest in recent years due to its influence on stream morphology and fluvial processes (Bilby, 1984; Gregory et al., 1985; Beschta and Platt, 1986; Cherry and Beschta, 1989; Gippel, 1989), macroinvertebrates (Anderson et al., 1978; Benke et al., 1985; Benke and Parsons, 1990), fish (Hickman, 1975) and ecosystem dynamics (Harmon et al., 1986; Hauer, 1989). Debris dams and other LWD formations retain leaf litter and other detritus in streams and allow
processing by invertebrates (Prochzaka et al., 1991). LWD accumulations are prominent features along most natural streams and may provide substrate for most of the invertebrate biomass in sand-bed rivers, such as those common to the Coastal Plain of the south-eastern USA (Benke et al., 1985) and the desert south-west of the USA (Minckley and Rinne, 1985). Cover, depth and velocity patterns associated with LWD formations are essential elements of fish habitats (Hortle and Lake, 1983; Angermeier and Karr, 1984).

Frequently, LWD is removed from stream channels to increase conveyance, control erosion, or reduce navigation hazard. LWD removal may be the most common form of stream habitat modification in the USA. Deleterious effects of debris removal ('clearing and snagging') have been at least qualitatively appreciated for many years (Little, 1973; Marzolf, 1978; Yorke, 1978; Bilby, 1980). Guidelines for selective removal of LWD formations (International Association of Fish and Wildlife Agencies (IAFWA), 1983; Shields and Nunnally, 1984) have been proposed to reduce adverse effects of LWD removal on stream habitats, but the effectiveness of the guideline approaches as conservation practices have not been evaluated. Due to the ubiquity of LWD removal projects, use of these guidelines may become one of the most widely practised stream habitat conservation strategies. When planning and designing LWD removal projects, stream managers must balance ‘engineering’ (e.g. flood control, drainage or navigation) and habitat conservation objectives. Quantitative, rational techniques for striking this balance are currently lacking.

The purpose of this paper is to describe effects of selective LWD removal on channel conveyance and physical aquatic habitats of a sand-bed river, with an overall objective of providing a basis for impact assessment and conservation strategy development for similar rivers and streams. This objective required development of a technique for predicting changes in Darcy friction factors due to LWD removal. Stream properties which were of interest included LWD density, which was treated as the primary independent variable, Darcy friction factor, aquatic habitat diversity, and bed sediment size and carbon content. Debris density, hydraulic roughness (Darcy friction factor), and velocity distributions were measured for reaches ~1.5 km long at low, moderate, and near-bankfull stages, and aquatic habitat (depth, velocity, and substrate distributions) was sampled at base flow.

**PREDICTION OF EFFECTS OF LWD REMOVAL ON FRICTION FACTOR**

Planning and design of an LWD removal project that will be performed using selective removal guidelines should include quantification of the physical effects of incremental LWD removal. In particular, reliable yet inexpensive methods for predicting the variation of channel friction factor with LWD density are needed for planning-level hydraulic analyses. Published friction factors for severely obstructed channels are three to four times larger than for those free of significant LWD (Shields and Nunnally, 1984). Few observations of friction factor before and after LWD removal are available; reported reductions range from 10 to 80% (US Engineer Office, Mobile, Alabama, 1940; Gippel, 1989). Techniques currently employed for determining hydraulic effects of LWD removal rely on estimation and engineering judgement (Chow, 1959; Barnes, 1967). Engineers select friction factors based on experience by comparing the channel in question to photographs or tabular descriptions in standard references such as Chow or Barnes. These photographs generally depict either channels with virtually no LWD or with evidently high (but unspecified) LWD densities.

Petryk and Bosmajian (1975) presented an equation for predicting coefficients (Manning’s $n$) for open channels where vegetation plays a major role in the flow resistance (e.g. broad, heavily vegetated floodplains, roadside drainage ditches with thick, tall vegetation, and canals choked with aquatic vegetation). The equation was derived from first principles by assuming that flow conditions are uniform and that the approach velocity to each plant stem is equal to the mean velocity. By applying reasoning similar to that of Petryk and Bosmajian to uniform steady flow through a straight channel reach where LWD plays a major role in flow resistance, the total friction factor can be expressed as
EFFECTS OF LARGE WOODY DEBRIS REMOVAL FROM RIVERS

\[ f_t = f_b + f_d \]

where

- \( f_t \) = total Darcy–Weisbach friction factor
- \( f_b \) = boundary friction factor excluding LWD effects, and
- \( f_d \) = friction factor due to LWD.

The boundary friction factor \( f_b \) can be estimated using curves provided by Lovera and Kennedy (1969) and Alam and Kennedy (1969) or other standard methods. The friction factor due to LWD, \( f_d \), may be determined by expressing the energy lost per unit channel length due to debris as the result of drag on a series of solid obstructions (Petryk and Bosmajian, 1975):

\[ h_{Ld} = f_d (L/4R) (V^2/2g) \]

(2)

\[ = K_d (V^2/2g) \]

(3)

\[ = C_d D_A L (V^2/2g) \]

(4)

which implies that

\[ f_d = 4R C_d D_A \]

(5)

where

- \( h_{Ld} \) = head loss, due to debris [L]
- \( L \) = reach length [L]
- \( R \) = mean hydraulic radius, assumed equal to depth [L]
- \( V \) = mean water velocity [LT^{-1}]
- \( g \) = acceleration of gravity [LT^{-2}]
- \( K_d \) = dimensionless loss coefficient
- \( C_d \) = drag coefficient for LWD, assumed equal to 1.0 (Petryk and Bosmajian, 1975), and
- \( D_A \) = roughness concentration due to LWD [L^{-1}].

\( D_A \) may be thought of as the average roughness concentration (Li and Shen, 1973) per unit length. It is given by

\[ D_A = \frac{\sum_{i=1}^{n} A_i}{BRL} \]

(6)

where

- \( A_i \) = cross-sectional area of ith debris formation in plane normal to flow, and
- \( B \) = average water-surface width.

STUDY SITE AND DISTURBANCE HISTORY

The South Fork Obion River is part of a 13000 km² agricultural watershed that is tributary to the left descending bank of the Mississippi River in western Tennessee. Regional geology is characterized by unconsolidated and highly erosive Quaternary formations. Wisconsin loess dominates surficial geology, and there are no bedrock controls of stream base level. Watershed relief is low, and the narrow floodplains were
wetlands traversed by sinuous channels of low gradient prior to initial channelization and drainage. Straightening and dredging of channels throughout the basin have occurred periodically since about 1900 (Simon and Hupp, 1986; Simon, 1989).

The study area was located between River Kilometers (RKS) 37.1 and 45.8 of the South Fork Obion River (Figure 1). Upstream drainage area was about 927 km². The sand-bed channel was straight, and cross-sections were trapezoidal and uniform with top widths ranging from 18 to 23 m and maximum depths from 4 to 5 m. At the outset of the study, banks were steep but stable, and were composed of clay and silt. At base flow, water surface widths were 12 to 17 m, and mid-channel depths ranged from 0.6 to 1.5 m. Photographs of the study area are presented by Smith et al. (in press).

The study area was well suited for our research. The disturbance history and present condition of the South Fork Obion River are typical of many streams in the south-eastern United States. The channel was flanked by hardwood forests. Riparian species found along adjacent and downstream reaches in the same watershed included boxelder (Acer negundo), river birch (Betula nigra), sycamore (Platanus occidentalis), bald cypress (Taxodium distichum) and various species of oaks (Quercus spp.) and elms (Ulmus spp.) (Hupp, 1986; Simon and Hupp, 1987). Tree ages ranged from 25 to 45 years (Simon and Hupp, 1987). An LWD removal project was under way at the time, and selective removal guidelines were employed. Prior to clearing, LWD formations occupying more than one-fifth of the cross section were common. Hydrologic variations were damped due to ponding upstream of a major LWD formation that completely blocked the channel upstream of the study area, creating near-steady flow conditions that facilitated dilution gauging. Study reaches (Figure 1) were free of major tributary inflows. The straight channel planform simplified partitioning hydraulic roughness into components due to LWD and the channel boundary.

Figure 1. Location of study reaches. Data were collected between October 1989 and August 1990. Reach 1 was cleared in the fall of 1989 just prior to study initiation. Reach 2 was cleared in June-July 1990. Reach 3 was cleared in May 1990.
The study channel was initially straightened in the early 1900s. Additional dredging occurred from the mouth to RK 8.3 and from RKS 13.3 to 15.4 in 1967 and 1969 respectively (Barstow, 1971; Smith and Badenhop, 1975). LWD removal was performed just downstream from the study area (RKS 9.6 to 36.8) between 1976 and 1978 (personal communication, Andrew Simon, US Geological Survey, Nashville, Tennessee). From 1978 to 1985 channel modification, including LWD removal, was halted by litigation throughout the Obion-Forked Deer Basin. After 1985, channel modifications were performed in compliance with guidelines similar to IAFWA (1983) (Governor's West Tennessee Natural Resources Task Force, 1985).

Instability of reaches downstream of the study area following the 1967-69 channelization has been described in some detail by Simon (1989) and Simon and Hupp (1986), but the study area was relatively stable during this period. Cross-section plots and specific gauge records for locations downstream of the study area indicated headward-progressing bed degradation (personal communication, Andrew Simon, US Geological Survey, Nashville, Tennessee). About 1 m of degradation occurred between RKS 26.9 and 30.7 between 1978 and 1983 and about 0.6 m of lowering occurred at the lower end of the study area (RK 37.1) between 1980 and 1983. However, cross-section surveys taken at the upper end of the study area (RK 45.6) in 1969, 1979 and 1983 showed no evidence of degradation. At the outset of this study, channel banks in the study area were quite stable, and old disposal piles from the turn-of-the-century channel work were still evident along the edges of the main channel in 1990. Upstream of the study area, specific gauge analysis for RK 55.2 showed a slight aggradation of 0.4 m between 1967 and 1981.

An LWD removal project was in progress within the study area while data were being collected. Project design and construction were according to the aforementioned guidelines. The work was performed by a crew of seven men using a D-3 bulldozer with a cable and winch, chainsaws, and a small flat bottom boat with motor. Work was limited to removal of trees and LWD from the bottom and banks of the channel. Logs embedded in the channel were not removed if they were aligned with the flow. No rooted trees, whether alive or dead, were cut unless they were leaning at an angle of 20° or more off vertical or unless they had severely undercut or damaged root systems. Access and material disposal were limited to one side of the channel to minimize disturbance of riparian habitat. The LWD was placed in windrows parallel to the channel in a manner that prevented re-entry into the channel. No channel excavation (i.e. sediment removal) was performed. Cost for the project was about US$29700 km⁻¹.

**DATA COLLECTION**

**Density of LWD**

Several investigators have described labour-intensive techniques for determining stream LWD density (e.g. Wallace and Benke, 1984; Robison and Beschta, 1990). These methods require measurement of the diameter of each piece of LWD within a channel reach or a large fraction of the LWD within a reach. Less rigorous methods were described by Hauer (1989), who measured the dimensions of LWD formations in 10 m channel segments (five segments per site) and by Zimmer and Bachman (1976), who reported the number of debris formations per unit channel length without regard to formation size. Due to our study objectives and funding constraints, we required a method that would be suitable for determining the LWD density in reaches long enough for measurement of macroscale hydraulic roughness (say > 1 km) and easy enough to require only several man-hours per km of channel. Due to the dense floodplain vegetation in the study area, the channel was only partially visible from the air and access along the top of banks was very limited. Therefore, a method for estimating LWD density based upon a visual survey from within the channel was developed.

LWD data were obtained for three straight reaches, each approximately 1.5 km long (Figure 1) at stages ranging from near-bankfull to base flow. Nine LWD surveys were performed prior to LWD removal, and
six surveys were performed after LWD removal. LWD surveys consisted of counting all LWD formations with an area in the plane of the water surface larger than about 1 m². In order to minimize errors due to observer subjectivity, the same person performed all surveys for the study. Each formation was assigned to one of nine size categories. Size classifications were based on visual estimates of the maximum length of each LWD formation below the plane of the water surface in directions perpendicular and parallel to the primary flow direction. Size categories were based on the reach mean water surface width, B. The following intervals were used for size classification: in the direction perpendicular to the primary flow, each formation was classified as smaller than 0.25B, more than 0.25B but less than 0.5B, or more than 0.5B. In the direction parallel to flow, each formation was classified as smaller than 0.5B, more than 0.5B but less than B, or more than B. Since there were three possible size scores in each of two dimensions, there were a total of nine size categories.

Data from LWD surveys were used to compute roughness concentration \( D_A \) (as defined by equation 6 above), dimensionless density (LWD volume/unit water volume), LWD volume per unit streambed area, and LWD frequency (formations/unit channel length). It was assumed that the vertical submerged dimension of each LWD formation was equal to the reach mean depth. Therefore for the \( i \)th LWD formation, \( A_i \) was set equal to the midpoint of the size interval for the direction perpendicular to flow multiplied by the reach mean depth, \( R \). For example, a formation measuring roughly 0.4B (perpendicular to flow) by 0.8B (parallel to flow) would have \( A_i = 0.375BR \). Since \( D_A = \sum A_i / (BRL) \), \( BR \) may be dropped from both numerator and denominator. Dimensionless density (volume of LWD per unit water volume) and volume of LWD per unit streambed area were computed by dividing \( \sum V_i \) by \( BRL \) and \( BL \), respectively, where \( V_i = \) submerged volume of the \( i \)th debris formation = mean depth multiplied by the product of the midpoints of the two size intervals. For the example previously given, \( V_i = R(0.375B \times 0.75B) \). Trees and stumps on banks that projected into flow were counted, and their contribution to roughness concentration \( (A_i) \) and LWD density \( (V_i) \) were computed using estimated submerged lengths and means of samples of their diameters measured using tree calipers.

Stream hydraulic characteristics

Dilution gauging techniques were used to obtain discharge, time-of-travel frequency distributions, and Darcy friction factors for the three 1.5 km reaches (Figure 1). Nine slug-injection fluorescent dye tests were conducted during flows ranging from 3.9–41.3 m³s⁻¹ in uncleared reaches, and six tests were run in cleared reaches during flows ranging from 3.6–53.2 m³s⁻¹. Dosage requirements, preparation of the dye standards, and procedures for calibration of the fluorometer were determined using standard procedures (Hubbard et al., 1982). Tests were conducted at the downstream reach first and then proceeded upstream. Emergent bars and riffles were not observed during dye tests. An appropriate volume of Rhodamine WT dye was instantaneously released at the upper end of each reach from a small boat. A flow-through fluorometer was set up at the lower end of the reach and used to measure dye concentration with time. During each dye test, water surface elevations were recorded using temporary staff gauges that were installed at the upstream and downstream ends of each reach, and water surface widths were measured at five to 12 regularly spaced cross-sections. Dye curves were used to compute discharge, and mean depth was computed by dividing the discharge by mean width multiplied by reach length. Mean velocity was computed by dividing reach length by mean travel time. Water surface slope was determined from gauge readings and reach length, and Darcy friction factors were determined from a uniform flow equation.

Sediment and organic matter retention

Bilby and Likens (1980) and Coleman and Dahm (1990) noted the importance of LWD formations in trapping and retention of organic matter (which provides a basis for some food chains) and sediments finer than sand. In sand-bed rivers fine, cohesive sediments support much higher levels of invertebrate
biomass density than adjacent sands (Shields and Milhous, 1992). LWD influence on channel retentive capability was measured by converting normalized dye curves (which are time-of-travel distributions) to velocity distributions by dividing reach length by travel times. The 90 percentile velocities, which represent the maximum velocity for the slowest-moving 10% of the dye cloud, were compared for cleared and uncleared reaches for a range of flows. In addition, samples of bed material were also collected from five to eight cross-sectional transects in each of the three reaches and returned to the laboratory for sieve analysis (both fall and spring) and determination of organic content (combustible matter) (spring only). Four to five samples were collected at equidistant points at each transect in the fall and from the channel centre line (in the more homogeneous cleared reach) and three (in the uncleared reaches) equidistant points at each transect in the spring. The presence or absence of cover (LWD formations) adjacent to bed sample collection points was recorded. Single-classification model II analyses of variance (ANOVA) were performed for sample median bed material size \( (D_{50}) \) and carbon content using reaches and cover as treatments, and two-way unequal ANOVA was performed using reach and cover as classifications.

**Aquatic habitat**

An approach similar to one described by Gorman and Karr (1978) was used to characterize physical aquatic habitats at low flow. Five to eight cross-sectional transects at water-surface-width intervals were established in each of the three 1.5 km study reaches at locations judged to be typical of the entire reach. Velocity, depth, substrate (surficial bed material), and cover were measured or classified at points spaced at 0.9 m intervals along each transect. Depths were determined using wading rods and sounding lines, while velocities were measured at 0.6 depth using Price and Marsh-McBirney current meters. Data were collected by wading or, when depths exceeded about 1.2 m, from small boats. Predominant bed material type was visually categorized as clay/silt, sand, gravel, leaf litter, or vegetation (five categories) at each measurement point in the field. The presence or absence of cover (two categories) was also noted for each point. Cover classifications were based on visual inspection of the spherical volume with 0.5 m of each measurement point. Points coinciding with or within 0.5 m of logs, log jams, undercut banks, or overhanging canopy were classified as 'with cover'. Spring data were collected from reach 1 after clearing and from reach 2 prior to clearing. Fall data were collected from reach 1 after clearing and from reaches 2 and 3 before clearing.

Means and standard deviations of depth and velocity were computed for cleared and uncleared reaches and for points with and without cover. Single-classification model II analyses of variance (ANOVA) were performed for depth and velocity data using reaches and cover as treatments, and two-way unequal ANOVA was performed using reach and cover as classifications. Shannon diversity indices (Gorman

<table>
<thead>
<tr>
<th>Score</th>
<th>Depth (cm)</th>
<th>Velocity (cm s(^{-1}))</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 5</td>
<td>&lt; 1</td>
<td>Clay/silt</td>
</tr>
<tr>
<td>2</td>
<td>5–20</td>
<td>1–5</td>
<td>Sand</td>
</tr>
<tr>
<td>3</td>
<td>20–50</td>
<td>5–20</td>
<td>Gravel</td>
</tr>
<tr>
<td>4</td>
<td>50–80</td>
<td>20–40</td>
<td>Leaf litter</td>
</tr>
<tr>
<td>5</td>
<td>80 or greater</td>
<td>40 or greater</td>
<td>Vegetation</td>
</tr>
</tbody>
</table>
Table 2. Comparison of measured large woody debris densities for uncleared and cleared reaches of the South Fork Obion River with published values for other streams

<table>
<thead>
<tr>
<th>LWD density units</th>
<th>South Fork Obion River</th>
<th>From literature</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncleared LWD density</td>
<td>Cleared LWD density</td>
<td>Drainage area(^a), km(^2)</td>
</tr>
<tr>
<td>Roughness concentration, (D_A) km(^{-1})</td>
<td>1.2–9.2</td>
<td>5.8–12.5</td>
<td>92–110</td>
</tr>
<tr>
<td>Formations/km channel</td>
<td>35–58</td>
<td>6–58</td>
<td>0.6–34.4</td>
</tr>
<tr>
<td>(m^3/ha) stream bed</td>
<td>430–940</td>
<td>90–330</td>
<td>168</td>
</tr>
<tr>
<td>(m^3/ha) stream bed</td>
<td>110</td>
<td>See note d below</td>
<td>See note d below</td>
</tr>
<tr>
<td>(m^3/ha) stream bed</td>
<td>2(^a)</td>
<td>See note d below</td>
<td>Steel Cr, SC, USA</td>
</tr>
<tr>
<td>(m^3/m^3) water</td>
<td>0.0316–0.0869</td>
<td>0.0062–0.0405</td>
<td>0–0.233(^b)</td>
</tr>
</tbody>
</table>

\(^a\)LWD density depressed due to many years of flow augmentation by a thermal discharge.

\(^b\)Reported as 'area of snags as % of total area'. Equivalent to our dimensionless density \((m^3/m^3)\) since we assumed vertical dimension of LWD formations = mean depth.

\(^c\)For comparison with our study site drainage area ~ 927 km\(^2\).

\(^d\)Meyer’s Branch and Steel Creek are second order tributaries of a 91 km\(^2\) catchment. They drain areas of nearly identical size.
and Karr, 1978; Magurran, 1988) were calculated for each of the three reaches using depth, velocity, and substrate data from the transects. For purposes of Shannon function computations, each sampled point was assigned a digital score based on the scheme in Table 1. The category boundaries in Table 1 are a modification of those proposed by Gorman and Karr (1978) based upon fish habitat preferences in similar-sized, disturbed, warmwater streams in the mid-southeastern United States (Shields and Hoover, 1991). Shannon indices were computed using combined digital scores for depth and velocity (25 possible categories) and depth, velocity, and substrate (125 possible categories). Shannon indices for cleared and uncleared reaches were compared using a two-tailed t-test for unpaired data (Magurran, 1988).

RESULTS

Density of LWD

LWD surveys performed prior to LWD removal yielded roughness concentration values that ranged from 5.8 to 12.5 km⁻¹ and averaged 9.0 km⁻¹. Six surveys performed after LWD removal yielded roughness concentrations that ranged from 1.2 to 9.2 km⁻¹ and averaged 4.7 km⁻¹. The ratio of LWD volume to water volume averaged 0.0545 for uncleared reaches and 0.0225 for cleared reaches. Density values for reaches 2 and 3 after clearing were higher than for reach 1 after clearing, primarily due to drift formations exposed by bed scour following construction. In general, LWD density decreased as stages increased from low- to mid-bank elevation, but remained relatively constant from mid-bank to near bankfull. However, LWD formations that were submerged deeply enough to be invisible were not counted. Therefore, LWD density may have been underestimated.

Although the method of measuring LWD density used in this study was crude, the resulting values were comparable to data presented by other workers for lowland streams in temperate, sub-humid environments (Table 2). The roughness concentration values by Petryk and Bosmajian (1975) were for a channel with more living vegetation on the bed and banks than our study reaches. Streams studied by Zimmer and Bachman (1976) were about twice as steep and had about half the watershed area of our study area. Wallace and Benke (1984) used various techniques that involved measuring dimensions of individual LWD stems; since we used LWD formation dimensions without regard for the openings between stems our values are higher. Values reported by Hauer (1989) and by Hortle and Lake (1982) may reflect the relatively small size of sampled areas: the former measured dimensions of individual LWD formations in ten 10 m reaches, and the latter reported the percentage of stream area occupied by snags on three occasions in six 50 m reaches. Harmon et al. (1986) presented an extensive tabulation of published values of coarse woody debris (>10 cm diameter) in streams flowing through unmanaged temperate forests; values ranged from 2.5 to 4500 m³ha⁻¹. However, these data are almost entirely from upland or mountain streams draining watersheds smaller than 10 km², and many of the streams drain old-growth coniferous forests.

Measured friction factor

Measured Darcy–Weisbach friction factors ranged from 0.08 to 0.51 (Table 3) and were smaller for higher discharges (Figure 2). Decreasing flow resistance with increasing stage and discharge (within-bank flows)

<table>
<thead>
<tr>
<th>Flow condition</th>
<th>Uncleared</th>
<th></th>
<th></th>
<th>Cleared</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$Q$ (m³s⁻¹)</td>
<td>$D_A$ (km⁻¹)</td>
<td></td>
<td>$Q$ (m³s⁻¹)</td>
<td>$D_A$ (km⁻¹)</td>
</tr>
<tr>
<td>Low</td>
<td>0.42</td>
<td>3.9</td>
<td>9.82</td>
<td>0.11</td>
<td>3.9</td>
<td>8.23</td>
</tr>
<tr>
<td>Mid-bank to near bankfull</td>
<td>0.17</td>
<td>32</td>
<td>7.07</td>
<td>0.11</td>
<td>33</td>
<td>1.83</td>
</tr>
</tbody>
</table>
is in agreement with observations of Manning's $n$ for larger sand-bed rivers (Chow, 1959), similar channels in the south-eastern United States (Fasken, 1963), and other channels with significant LWD (Gregory et al., 1985; Gippel, 1989). Jarrett (1984) reported a similar trend for Manning's $n$ in high-gradient streams, but noted that the trend reversed at highest stages when dense bank vegetation was partially submerged. Beven et al. (1979) reported a hundred-fold decrease in Darcy's $f$ for a hundred-fold increase in discharge for a small, steep English stream.

LWD effects on $f$ were most pronounced at low flow (Figure 2). Evidently, LWD promotes energy dissipation by forcing flow contraction and pool formation processes that decrease as flows increase. Additionally, flexible branches may be forced prone at higher flows (Kouwen and Unny, 1973). Friction factors for cleared and uncleared reaches converged at higher flows. At flows $>10 \text{ m}^3\text{s}^{-1}$, mean values of $f$ for cleared ($n=4$, mean = 0.11) and uncleared ($n=6$, mean = 0.17) reaches were close but different at a confidence level of 99.93% ($t$-test for unequal variances; Mann-Whitney $U$ test gave similar results). Assuming bed slope remained constant, the difference in mean values of $f$ implies that LWD removal increased the amount of discharge conveyed by the channel at bankfull by about 25%. Similar observations of friction factor convergence at higher flows were reported by Hecht and Woyshner (1987) for Manning's $n$ values for reaches of the Pajaro River in California with forested and riprapped banks. Young (1991) reported that artificial LWD (wooden dowels) inserted in a small laboratory flume caused stage increases of 0.1–10% at constant discharge and bed slope. Stage rise was an exponential function of $\Sigma A_i/(BR)$ (see equation 6 above for definition of variables). Since his model was a fixed-bed rectangular cross-section flume and represented near-bankfull flow past one or two LWD formations, direct comparison with our results is difficult.

**Computed friction factor**

Darcy–Weisbach friction factors computed using the procedure described above ranged from 0.09 to 0.20.
Table 4. Means of computed values of Darcy-Weisbach friction factor, standard deviation of differences between computed and measured friction factors, and standard deviation of per cent difference between computed and measured values

<table>
<thead>
<tr>
<th>Flow condition</th>
<th>Uncleared</th>
<th>Cleared</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f$</td>
<td>SD of error</td>
</tr>
<tr>
<td>Low</td>
<td>0.20</td>
<td>—</td>
</tr>
<tr>
<td>Mid-bank to near bankfull</td>
<td>0.15</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Standard deviations not shown for low flow since $n=2$ for uncleared and for cleared.

(Table 4). Computed values of $f$ differed from measured values by $-61$ to $+101\%$ and were most accurate for mid- to near-bankfull stage conditions (for flows $\geq 10 \text{ m}^3\text{s}^{-1}$ errors ranged from $-33$ to $+19\%$ in cleared reaches and from $-35$ to $+12\%$ in uncleared reaches). Errors were larger from low flows because the method used to compute $f$ accounts only for energy losses due to grain, bed form, and LWD roughness, but not local losses due to expansion and contraction which are increasingly important at low flow (Miller and Wenzel, 1985). Computed values were closer to measured values for cleared reaches (S.D. of errors $= 0.045$) than for uncleared reaches (S.D. of errors $= 0.11$).

**Velocity distributions**

Means and variances of velocity distributions derived by dividing reach lengths by dye cloud travel times increased with increasing discharge. During flows $\geq 18 \text{ m}^3\text{s}^{-1}$, a very small percentage of uncleared reach

![Figure 3. 90-percentile velocity versus discharge for cleared and uncleared reaches. The 90-percentile velocity is equal to the reach length divided by the time required for 90% of a slug injection of dye to pass through the reach ($T_{90}$). • uncleared reaches; ○ cleared reaches.](image-url)
velocities exceeded 1 ms\(^{-1}\), but more than half of the velocities in cleared reaches exceeded 1 ms\(^{-1}\). For approximately equivalent discharges, mean velocities were less for uncleared reaches. The velocity of the slowest-moving 10% of the dye cloud \(V_{90}\) was used as an indicator of the relative ability of cleared and uncleared reaches to trap and retain fine sediments and particulate organic matter. Not surprisingly, \(V_{90}\) was directly related to discharge (Figure 3). Uncleared reaches were more retentive at low flows but not at high flows. For the four measurements at flows approximately equal to 4 m\(^3\)s\(^{-1}\), the two \(V_{90}\) values in the cleared reach were 50% greater than the two values for uncleared reaches (means of 38 and 25 cm s\(^{-1}\), see Figure 3). For discharges >10 m\(^3\)s\(^{-1}\), \(V_{90}\) for cleared reaches \((n = 4, \text{ mean } = 71 \text{ cm s}^{-1})\) was not significantly larger than for uncleared reaches \((n = 6, \text{ mean } = 63 \text{ cm s}^{-1})\) \((p = 0.38, t\text{-test for unequal variances}; p = 0.86, \text{ Mann-Whitney } U \text{ test})\). \(V_{90}\) was inversely related to measured Darcy–Weisbach friction factor \((r = -0.61)\).

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**Figure 4.** Cumulative frequency distributions for depth and velocity for data collected in October-November 1989 and May 1990 in reach 1 (cleared) and reaches 2 and 3 (uncleared). — cleared; —— uncleared.
Table 5. Means and standard deviations of depth, velocity, and median bed sediment size for cleared and uncleared reaches of the South Fork Obion River. ns = not sampled

A. Data grouped by 1.5 km study reach. Analysis of variance indicated reaches had significantly different depths, velocities and bed material sizes at the 99% confidence level with the exception of bed material in the fall

<table>
<thead>
<tr>
<th>Season</th>
<th>Reach</th>
<th>Condition</th>
<th>Depth (cm)</th>
<th>Velocity (cm s⁻¹)</th>
<th>$D_{50}$ (mm)</th>
<th>Per cent finer than sand</th>
<th>Per cent organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>mean</td>
<td>SD</td>
<td>mean</td>
<td>SD</td>
<td>mean</td>
</tr>
<tr>
<td>Fall</td>
<td>1</td>
<td>Cleared</td>
<td>84</td>
<td>17</td>
<td>39</td>
<td>14</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Uncleared</td>
<td>82</td>
<td>36</td>
<td>32</td>
<td>20</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Uncleared</td>
<td>93</td>
<td>37</td>
<td>26</td>
<td>13</td>
<td>0.27</td>
</tr>
<tr>
<td>Spring</td>
<td>1</td>
<td>Cleared</td>
<td>133</td>
<td>26</td>
<td>49</td>
<td>22</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Uncleared</td>
<td>102</td>
<td>34</td>
<td>37</td>
<td>24</td>
<td>0.44</td>
</tr>
</tbody>
</table>

B. Data points grouped based on cover presence within a 0.5 m radius. Analysis of variance indicated differences in depth and velocity were significant at the 99.9% confidence level. Fall median bed sizes were different at the 98% level; spring bed sizes were not significantly different

<table>
<thead>
<tr>
<th>Season</th>
<th>Sampled points</th>
<th>Depth (cm)</th>
<th>Velocity (cm s⁻¹)</th>
<th>$D_{50}$ (mm)</th>
<th>Per cent finer than sand</th>
<th>Per cent organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean</td>
<td>SD</td>
<td>mean</td>
<td>SD</td>
<td>mean</td>
</tr>
<tr>
<td>Fall</td>
<td>Without cover</td>
<td>94</td>
<td>27</td>
<td>39</td>
<td>13</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>With cover</td>
<td>73</td>
<td>35</td>
<td>21</td>
<td>18</td>
<td>0.31</td>
</tr>
<tr>
<td>Spring</td>
<td>Without cover</td>
<td>119</td>
<td>32</td>
<td>44</td>
<td>34</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>With cover</td>
<td>84</td>
<td>34</td>
<td>28</td>
<td>22</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Physical habitat

Cross sections within cleared reaches were trapezoidal, and velocity patterns were symmetrical about the channel centreline. In contrast, data from uncleared reaches displayed considerable lateral variation in depth and velocity within sections and variation in width between sections.Uncleared reaches provided considerably more aquatic surface area with relatively shallow depth and reduced velocity (Figure 4). In the fall, only 22% of the points in the cleared reach had velocities less than 30 cm s\(^{-1}\), while 55% of the points in the uncleared reaches had velocities less than 30 cm s\(^{-1}\). The influence of debris on velocity persisted at higher stages in the spring, as 19 and 40% of the points in the cleared and uncleared reaches respectively had velocities less than 30 cm s\(^{-1}\). Uncleared reaches had greater mean widths than cleared reaches, which is consistent with continuity considerations.

As expected, cover was more common in uncleared reaches. In the fall, only 24% of the sampled points in the cleared reach had some type of cover, either small logs (11%) or undercut banks (12%), while 44% of the points in the uncleared reaches had some type of cover (small logs, log jams, undercut banks, or canopy). Only 8 and 22% of the points in the cleared and uncleared reaches, respectively, had cover in the spring, possibly because embedded logs were obscured by higher stages. Beds of all three reaches were sand: 92% of all substrate classifications were sand, but a few points in uncleared reaches were classified as clay/silt or vegetation.

Depth and velocity were subjected to two-way ANOVA using reaches (Table 5A) and cover (Table 5B) as treatments. Cover was classified as present or absent. Variation in depth and velocity due to reach and cover was statistically significant at the 99.99% confidence level. However, variations in depth and velocity due to interaction of reach and cover classification were not statistically significant, indicating that the local effects of remnant cover in cleared reaches were similar to cover effects in uncleared reaches. Evidently habitat characteristics near remnant LWD in cleared reaches were similar in quality to those in uncleared reaches. However, clearing greatly reduced the quantity of the low-velocity habitat created by LWD.

Bed composition

Bed material in all three reaches was sand but was finer in the uncleared reaches and at sampling points adjacent to cover (Table 5). Organic matter (as a percentage of dry weight) and median grain size were slightly higher in the cleared reach than in the uncleared reach, but these differences were not statistically significant. The mean percentage of sediment finer than sand size was four times greater in the uncleared reach than in the cleared reach (4.8 as opposed to 1.2%), but this difference was partially due to a single sample from the uncleared reach with an extremely high fines content (51%). Sediment samples collected from sampling points with cover had mean \(D_{50}\) values that were 56% higher, respectively, than points without cover. Organic content was positively correlated with median grain size \((r^2 = 0.585, p = 0.0001)\), but not % fines \((r = 0.126, p = 0.46)\). Conversely, Parker (1989) performed in-stream experiments with wire baskets filled with sediments coarser than the sands we studied (gravel, pebbles, cobbles, and mixtures) and found that the smallest substrate (gravel) collected the greatest quantity of fine (<1 mm) organic matter.

Shannon indices

Shannon indices indicated higher levels of physical habitat diversity associated with LWD (Table 6). Fall indices based on depth, velocity, and substrate for uncleared reaches averaged 28% higher than for the cleared reach, but the index for uncleared reach 3 (1.79) was not significantly greater than the index for the cleared reach (1.60). The spring index (depth-velocity) for the uncleared reach was 80% higher than the depth-velocity index for the cleared reach. Fall depth-velocity Shannon indices were higher than spring depth-velocity indices, presumably because higher flows and stages in the spring drowned out the influence of roughness elements such as LWD on depths and velocities. Decreasing physical heterogeneity with increasing discharge was
EFFECTS OF LARGE WOODY DEBRIS REMOVAL FROM RIVERS

Table 6. Shannon diversity indices \((H')\) and number of habitat categories \((S)\) observed in cleared and uncleared reaches of the South Fork Obion River. Diversity indices for reach 2 were different from indices for reaches 1 and 3 at the 98% confidence level in both fall and spring. Indices for reaches 1 and 3 were not significantly different.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Condition</th>
<th>Fall (DVSub) (H')</th>
<th>Fall (DV) (S)</th>
<th>Fall (DV) (H')</th>
<th>Fall (DV) (S)</th>
<th>Spring (DV) (H')</th>
<th>Spring (DV) (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cleared</td>
<td>1.60</td>
<td>13</td>
<td>1.49</td>
<td>11</td>
<td>0.95</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Uncleared</td>
<td>2.29</td>
<td>20</td>
<td>2.04</td>
<td>15</td>
<td>1.79</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>Uncleared</td>
<td>1.79</td>
<td>21</td>
<td>1.61</td>
<td>13</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*aBased on depth, velocity, and substrate.

Based on depth and velocity.

also indicated by dye test results (Figure 3). Physical habitat diversity was further quantified by counting the number of different habitat categories recorded for each study reach. This quantity, termed 'habitat richness' is found in columns headed with an ‘S’ in Table 6. Fall habitat richness values for uncleared reaches based on depth, velocity, and substrate averaged 21 out of a possible maximum of 125, while cleared reach richness was only 13. Habitat types corresponding to categories with velocities less than 1 cm s\(^{-1}\) were generally present in uncleared reaches, but absent in cleared reaches. Habitats with clay/silt and vegetation substrates were not found in the cleared reach, but were present in uncleared reaches. Mean \(S\) values based on depth and velocity were 14 out of a possible maximum of 25 for uncleared reaches but only 11 for cleared reaches. Habitat types corresponding to categories with velocities less than 1 cm s\(^{-1}\) were generally present in uncleared reaches, but absent in cleared reaches.

DISCUSSION

Unfortunately, it was not possible for us to obtain reliable before and after data from the same reach. Our findings depend on comparison of adjacent cleared and uncleared reaches. Although these reaches were quite similar, uncontrolled variations doubtless were present. The simple procedures developed in this study for quantifying LWD density and its effect on channel resistance may be used for environmental impact assessment and planning-level hydraulic engineering analyses; however, considerable refinement and site-specific adaptation may be necessary. The method for prediction of channel roughness coefficients does not account for local losses due to bends or due to flow expansion and contraction at bridges, debris dams, or riffles. Our technique for determining roughness concentration yielded values that were reasonable in the light of published values for other streams that resulted from more labour-intensive measurement techniques. We did not collect detailed LWD density measurements that would have allowed us to assess the accuracy and precision of our technique.

Our results suggest that benefits of proposed LWD removal projects should be carefully analysed in the light of costs and environmental impacts. In channels similar to the one we studied, the flood control benefits of LWD removal may be modest. We found that removal of LWD from the study reaches decreased the Darcy–Weisbach friction factor for near-bankfull conditions by about one third and increased bankfull flow capacity by about one fourth. Furthermore, the difference in high-flow friction factors for the cleared and uncleared reaches may decline with time as LWD densities in cleared reaches recover. Inspection of the cleared study reaches following storms revealed additional LWD either from riparian trees falling into the channel or exposed in the bed as a result of scour. The LWD removal project in our study area was viewed by the constructing agency as a maintenance activity, and therefore was not subjected to benefit–cost analyses (personal communication, Mr Richard Swaim, Obion-Forked Deer Basin Authority, Jackson, Tennessee). Effects on channel hydraulics and habitats were not forecast.
Erosion triggered by LWD removal may increase channel maintenance costs. Although investigation of the LWD effects on channel stability was beyond the scope of this study, visual observation of bank erosion following LWD removal combined with evidence of headward-progressing degradation suggested that LWD removal may have triggered or exacerbated bed lowering through the upper portion of the study area. Similar observations of instability triggered by LWD removal have been reported by others (Bilby, 1984; Strom, 1950 cited in Gippel, 1989).

Our findings confirmed many of the intuitive suggestions by earlier workers (Marzolf, 1978; Yorke, 1978) regarding effects of LWD removal on habitats. Several impacts on physical aquatic habitat at base flow were measurable and statistically significant, even though the Stream Obstruction Removal Guidelines (IAFWA, 1983) were applied throughout project planning and implementation. Cleared reaches had greater depths, higher velocities, slightly coarser bed material, and were more uniform. Habitat surface area with velocity (at 0.6 depth) less than 30 cm s\(^{-1}\) was reduced by about 50\%, cover was reduced by 45 to 64\%; and flow heterogeneity as measured by 90-percentile velocity was reduced at low flow but was unchanged for high flows. Relative to reported Shannon diversity values based on depth, velocity, and substrate for unaltered, smaller streams, which range between 2.8 and 4 (Gorman and Karr, 1978; Schlosser, 1987), even the uncleared reaches had low levels of physical diversity. Removal of LWD depressed Shannon indices by an additional 30 to 80\%.

Mean LWD formation volume for cleared reaches was an average of almost 60\% lower than for uncleared reaches. Habitat characteristics adjacent to remnant LWD formations and other types of cover in cleared reaches were similar to those adjacent to LWD and cover in uncleared reaches, although far less abundant. These areas tended to be shallower and have lower velocities and finer bed material with more organic matter than those distant from cover. Cover reduction may be the most important factor in regard to LWD removal impacts on fish populations (Hickman, 1975; Gore and Johnson, 1980; Hortle and Lake, 1983; Angermeier and Karr, 1984), while loss of LWD surfaces used as substrate is likely to be the most important factor for macroinvertebrates (Benke et al., 1985), which has implications for higher trophic levels. Benke et al. (1985) reported that invertebrate assemblages on LWD are characterized by higher levels of species richness and diversity and by larger individuals than assemblages in adjacent sand beds. Although shifting sand may be densely inhabited by macroinvertebrates that have extremely high levels of biomass production, these animals are so small that their importance to higher trophic levels (i.e. fishes) is open to question. Preliminary analysis of benthic samples collected concurrently with our spring field study suggests that sediments under and immediately adjacent to LWD, which are finer, have higher levels of organic matter, and are sheltered from currents, tend to support larger organisms than adjacent sand beds (personal communications, B. Payne and A. Miller, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi).

Our findings were similar to those reported by Angermeier and Karr (1984) for effects of debris in small Illinois streams. They also observed that lower debris densities were associated with decreased occurrence of benthic organic litter and increased current velocity and proportion of sand bottom, but they found that debris removal decreased rather than increased depth. Results herein were also similar to those of Hauer (1989), who observed higher current velocities (20 to 30\%) and lower levels of benthic organic matter (50 to 97\%) in a South Carolina stream without significant LWD compared to a reference stream with LWD.

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