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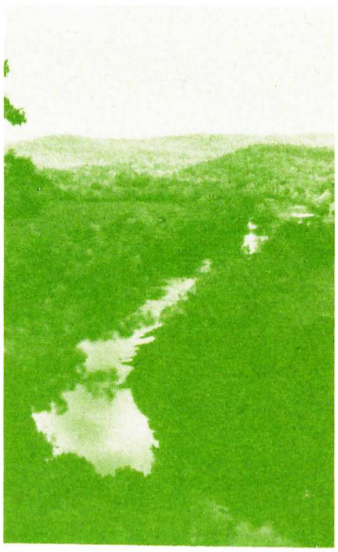

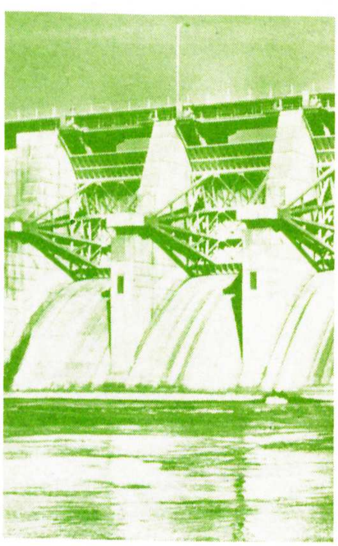

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INCREMENTAL EFFECTS OF LARGE WOODY DEBRIS REMOVAL ON PHYSICAL AQUATIC HABITAT

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13. ABSTRACT *(Maximum 200 words)*

Large woody debris (LWD) removal (also called clearing and snagging) is a widely employed practice. The LWD is removed from small channels to increase conveyance (i.e., reducing the stage and duration of high frequency flooding) and from large channels to eliminate navigation hazards. Complete removal of LWD can have detrimental effects upon stream habitats. Thus, a balance between habitat considerations and channel conveyance is necessary. Selective removal of bank and near-channel floodplain vegetation and channel obstructions is a means of accomplishing this balance.

The principal objective of this study was to investigate incremental effects of selective clearing and snagging on physical conditions and aquatic habitat in a sand bed river. The study was part of a larger program to develop techniques to quantify and predict incremental physical and biological effects of LWD removal. Long-term research objectives are to relate the densities and types of LWD formations in streams to specific biotic parameters, near-bank-full friction

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factor, and longitudinal dispersion as an indicator of the tendency of a channel reach to trap and hold fine particulate matter.

In this study, a simple method for quantifying LWD density and computing associated friction factors was developed and tested using data collected during a clearing and snagging project on the South Fork Obion River in western Tennessee. Physical conditions of both cleared and uncleared stream reaches were measured by collecting three types of data: LWD density, dye tracer tests (for computing reach mean hydraulic parameter), and physical habitat (depth, velocity, bed type, and cover) at selected transects. The LWD density was the important independent variable, while the dye tracer and physical habitat data were used to study macroscale and microscale effects of LWD, respectively.

Cleared reaches had LWD densities that were 50 to 90 percent less than those for uncleared reaches. Darcy friction factors were about 30 percent less for cleared reaches than for uncleared reaches at stages greater than mid-bank. Low-flow physical habitat diversity was reduced by LWD removal. Shannon indices were reduced by 30 to 80 percent; habitat area with velocity (at 0.6 depth) less than 1 fps (<0.3 m/sec) was reduced by about 50 percent, and flow heterogeneity as measured by travel time variance was reduced by 65 percent at low flow.

PREFACE

This report was prepared as part of Environmental Impact Research Program (EIRP) Work Unit 32555, "Effects of Selective Clearing and Snagging on Instream Habitat." The EIRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES). Dr. John Bushman and Messrs. David P. Buelow and Dave Mathis were the HQUSACE Technical Monitors.

Dr. F. Douglas Shields, Jr., and Mr. Elba A. Dardeau, Jr., Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), EL, each served as co-principal investigators of Work Unit 32555 jointly with Drs. Andrew C. Miller and Barry S. Payne, Aquatic Habitat Group (AHG), Environmental Resources Division, EL. Dr. Shields completed his work on this study after accepting a position with the USDA Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS. The field study and analysis of data for this report were planned in close coordination with AHG personnel and directed by Dr. Shields and Dr. Roger Smith, Center for River Studies, Memphis State University, while the latter was on an Intergovernmental Personnel Act assignment to WES. In addition to Drs. Shields and Smith and Mr. Dardeau, individuals involved in the field study and data analysis included Messrs. Thomas E. Schaefer, Jr., Anthony C. Gibson, and Terry L. Taylor, all of the WREG. This report was written by Drs. Smith and Shields and Messrs. Dardeau, Schaefer, and Gibson. Successful completion of the field study would not have been possible without the cooperation and assistance provided by Mr. Richard Swain and his staff of the Obion-Forked Deer Basin Authority and by personnel of Continental Engineering, Inc., Memphis, TN.

Work progressed under the general supervision of Dr. John J. Ingram, Chief, WREG; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL. Dr. Roger T. Saucier, EL, is the EIRP Program Manager. Technical reviewers included WES researchers, Dr. Payne, Mr. William A. Thomas, Hydraulics Laboratory, Dr. Paul R. Schroeder, WREG, in addition to Mr. Joe Willis and Dr. Scott Knight of the USDA National Sedimentation Laboratory.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
feet per mile	0.1893935	metres per kilometre
inches	25.4	millimetres
miles (US statute)	1.609347	kilometres
square feet	0.09290304	square metres
square miles (US statute)	2.589998	square kilometres

INCREMENTAL EFFECTS OF LARGE WOODY DEBRIS REMOVAL ON PHYSICAL AQUATIC HABITAT

PART I: INTRODUCTION

Background

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 (Andrus, Long, and Froelich 1988; Beschta 1979; Beschta and Platts 1986; Bilby 1984, 1985; Cherry and Beschta 1989; Gippel 1989; Gregory, Gurnell, and Hill 1985; Heede 1985; Keller and Swanson 1979; Marston 1982), macroinvertebrates (Anderson et al. 1978, Benke et al. 1985, Benke and Parsons 1990) and fishes (Angermeier and Karr 1984; Bryant 1983; Hickman 1975; Hortle and Lake 1983; MacDonald and Keller 1983; Salo and Cundy 1987; Sedell, Swanson, and Greogory 1985), and ecosystem dynamics (Harmon et al. 1986, Hauer 1989, Munn and Meyer 1990, Sedell and Froggatt 1984, Ward and Aumen 1986). Formations of LWD are prominent features along most natural streams (Appendix A). Frequently, LWD is removed from stream channels to increase conveyance, control erosion, or reduce navigation hazard. Deleterious effects of debris removal ("clearing and snagging") have been at least qualitatively appreciated for many years (Little 1973, Marzolf 1978, Yorke, 1978). Guidelines for selective removal of LWD formations (International Association of Fish and Wildlife Agencies (IAFWA) 1983, State of New York 1986 (see Appendix B) have been proposed to reduce adverse effects of LWD removal on stream habitats and channel stability. Shields and Nunnally (1984) and Headquarters, U.S. Army Corps of Engineers (1989), provide some guidance for design and implementation of a selective LWD removal project, but little information is available to facilitate prediction of selective LWD removal effects on physical habitat or near-bank-full friction factor.

Purpose

The purpose of this study was to describe effects of varying levels of LWD density on key aspects of physical aquatic habitat in medium-sized rivers.

A companion report describes a concurrent biological study (Payne and Miller in preparation). Physical parameters of interest in this study included depth, velocity, longitudinal dispersion, and bed material. In particular, the incremental effects of LWD removal on habitat character and heterogeneity were of interest. There were at least two secondary objectives: (a) to develop and demonstrate a method for quantifying LWD in a given river reach quickly and cheaply and (b) to relate the quantity of LWD to reach hydraulics. Hydraulic parameters were primarily those with potential biological significance and included the distribution of current velocities and hydraulic roughness.

Personnel planning and designing water resources projects involving LWD removal from streams should be able to use the information contained in this report to assess impacts of various alternatives. Alternatives could include varying levels of construction effort (LWD removal) and varying construction techniques (manual labor versus heavy equipment).

Scope

A medium-sized river obstructed by LWD and scheduled for a clearing and snagging construction project during the study period was identified and selected for field monitoring. Vegetation and woody debris were removed in accordance with "Stream Obstruction Removal Guidelines" (IAFWA 1983). Density of LWD for cleared and uncleared reaches was quantified using a procedure described herein. Physical habitat heterogeneity and bed sediment composition were determined for cleared and uncleared reaches at low flow. Effects of LWD removal on hydraulic roughness were determined by measuring Darcy friction factors for cleared and uncleared reaches over a range of discharges. With few exceptions, resource constraints precluded data collection from the same reach before and after clearing.

PART II: DATA COLLECTION AND ANALYSIS

Study Site and Disturbance History

The South Fork Obion River is part of a 5,000-square mile* agricultural watershed that is tributary to the left descending bank of the Mississippi River in western Tennessee. Watershed relief is low, and the narrow floodplains were wetlands traversed by sinuous channels of low gradient prior to initial channelization and drainage. 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. Straightening and dredging of channels throughout the basin has occurred periodically since about 1900 (Simon 1989, Simon and Hupp 1986).

The study area was located between river miles (RMs) 23.2 and 28.6 of the South Fork Obion River (Figure 1). Upstream drainage area was about 358 square miles. The sand bed channel was straight, and cross sections were trapezoidal and uniform, with top widths ranging from 60 to 75 ft and maximum depths from 12 to 15 ft (Figure 2). 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 40 to 55 ft, and mid-channel depths ranged from 2 to 5 ft. With one exception (noted below), emergent bars and riffles were not observed. Large woody debris formations occupying more than one fifth of the cross section were common. Hydrologic variations were damped because of ponding upstream of major LWD formations upstream of the study area.

The study reach was initially straightened in the early 1900s. Additional dredging occurred from the mouth to RM 5.2 and from RMs 5.2 to 6.0 in 1967 and 1969, respectively (Barstow 1971, Smith and Badenhop 1975). Clearing and snagging was performed just downstream from the study reach (RMs 6 to 23) between 1976 and 1978 (Simon and Woodside undated). Channel modifications throughout the Obion-Forked Deer Basin (including clearing and snagging) were halted by litigation from 1978 through 1985. Since 1985, channel modifications have been performed in compliance with guidelines specified by the Governors's West Tennessee Natural Resources Task Force (1985). These guidelines

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 6.

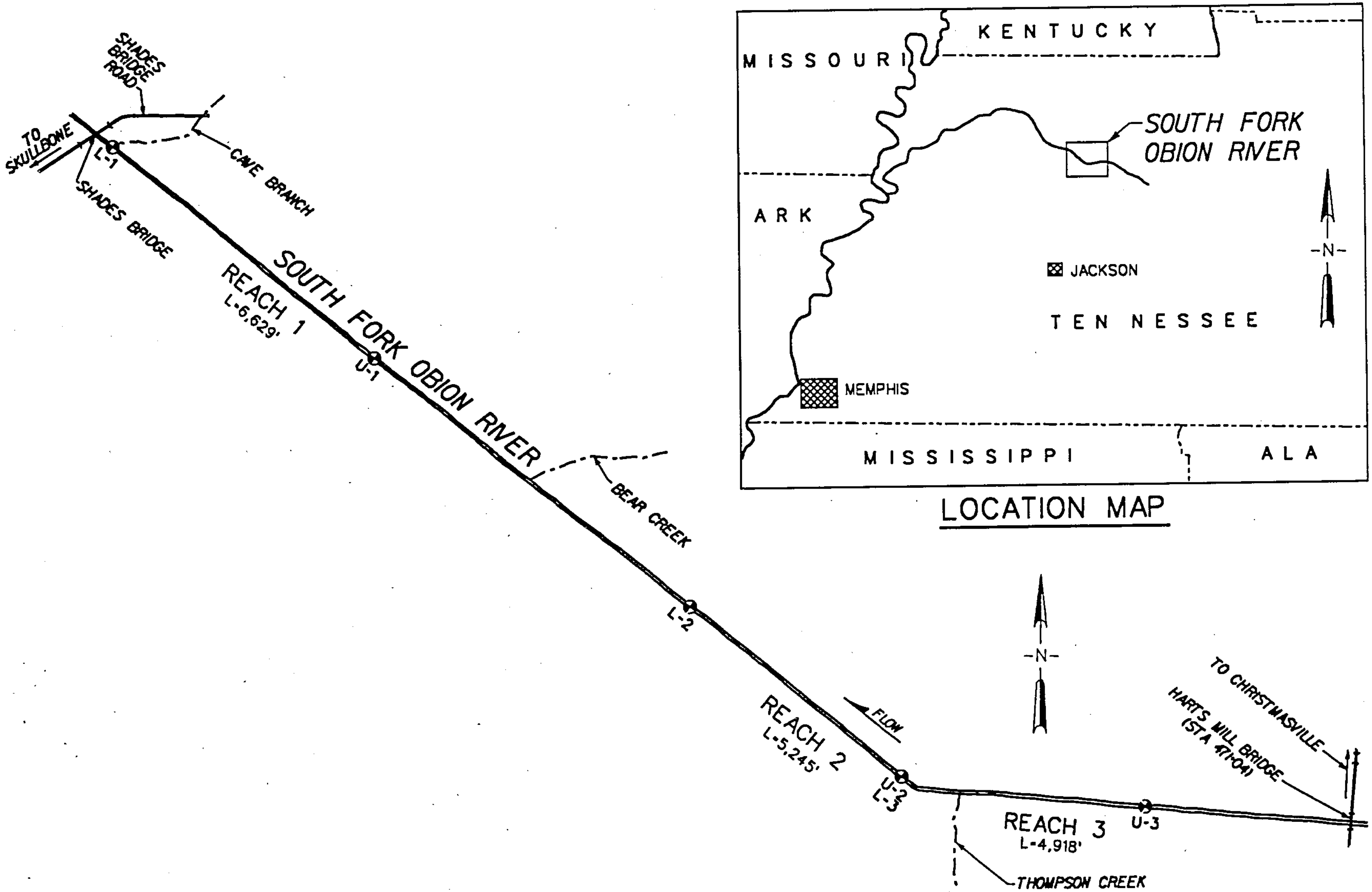

Figure 1. South Fork Obion River study area

Figure 2. South Fork Obion River. View from Harts Mill Bridge at upper end of project (see Figure 1)

are similar to those proposed by the IAFWA (1983) and to those presented in Appendix B.

Instability of reaches downstream of the study area because of the 1967-1969 channel modification has been described in some detail by Simon (1989) and Simon and Hupp (1986). However, at the outset of this study, channel banks were quite stable. Old disposal piles from the turn-of-the-century channel work were still evident along the edges of the main channel in 1990. Simon and Woodside (undated) examined cross-sectional plots and specific gage records and found evidence of headward-progressing bed degradation. About 3.5 ft of degradation occurred between RMs 16.8 and 19.2 between 1978 and 1983. About 2 ft of lowering occurred at the lower end of the study area (RM 23.2) between 1980 and 1983. However, cross-section surveys taken at the upper end of the study area (RM 28.5) in 1969, 1979, and 1983 showed no evidence of degradation. Specific gage analysis for RM 34.5 showed a slight aggradation of 1.3 ft 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 (Figure 3) with a cable and winch, chainsaws (Figure 4), and a small flat-bottom boat with motor. Work was limited to removal of trees and LWD from the bottom (Figure 5) and banks (Figure 6) 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 deg or more off vertical or 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 (Figure 7). The LWD was placed in windrows parallel to the channel in a manner to prevent reentry into the channel. No channel excavation (i.e., sediment removal) was performed. Approximately 3 miles or about one half of the main channel work was completed during the fall of 1989. The remainder of the work was completed in the spring and summer of 1990. Cost for the project was about $47,520 per mile.

Data Collection

Physical habitat data were collected between 31 October 1989 and 5 August 1990. Three types of data were collected: LWD density counts, fluorescent dye tests, and physical habitat measurements (depth, velocity, bed type, and cover) at selected transects. LWD density was the important independent variable, while the dye tracer and physical habitat data were used to study macroscale and microscale effects of LWD, respectively. Three different reaches, each approximately 1 mile long, were established for LWD density counts and fluorescent dye flow tests (Figure 1). One reach was located in the downstream portion of the area modified in the fall of 1989. The other two reaches were established in the middle and upper uncleared portions of the project.

Density of LWD

The manpower and cost requirements for detailed measurement and mapping of individual LWD formations would have been prohibitive. Access along the top bank was very limited because of dense woody riparian growth, a condition typical of many alluvial streams. Therefore, a method for estimating LWD density based upon a visual survey from a small boat was developed.

Figure 3. D-3 bulldozer used to clear the bank

Figure 4. Chain saws were used to selectively remove trees and woody debris

Figure 5. Large woody debris on the bottom of the channel protruding above the water surface

Figure 6. Large woody debris on the banks of the channel

Figure 7. Access road on side of channel designed to minimize disturbance to the riparian environment. Channel is to right edge of road just outside photo

LWD formations (Figure 8) were described using the classification system of Platts et al. (1987) supplemented with size criteria and an added category for streambank trees:

a. Type A - Collapsed bridge. Tree(s) fallen across the stream with section(s) of the tree(s) leaning against the bank(s); "within-bank" flows going under or over portions of the blockage.

b. Type B - Ramp. Tree(s) blocking a portion of the stream and leaning against one bank; "within-bank" flows going under or around one end of the blockage.

c. Type C - Drift. Tree(s) and woody debris blocking a portion of the stream; "within-bank" flows occurring freely around both ends of the blockage.

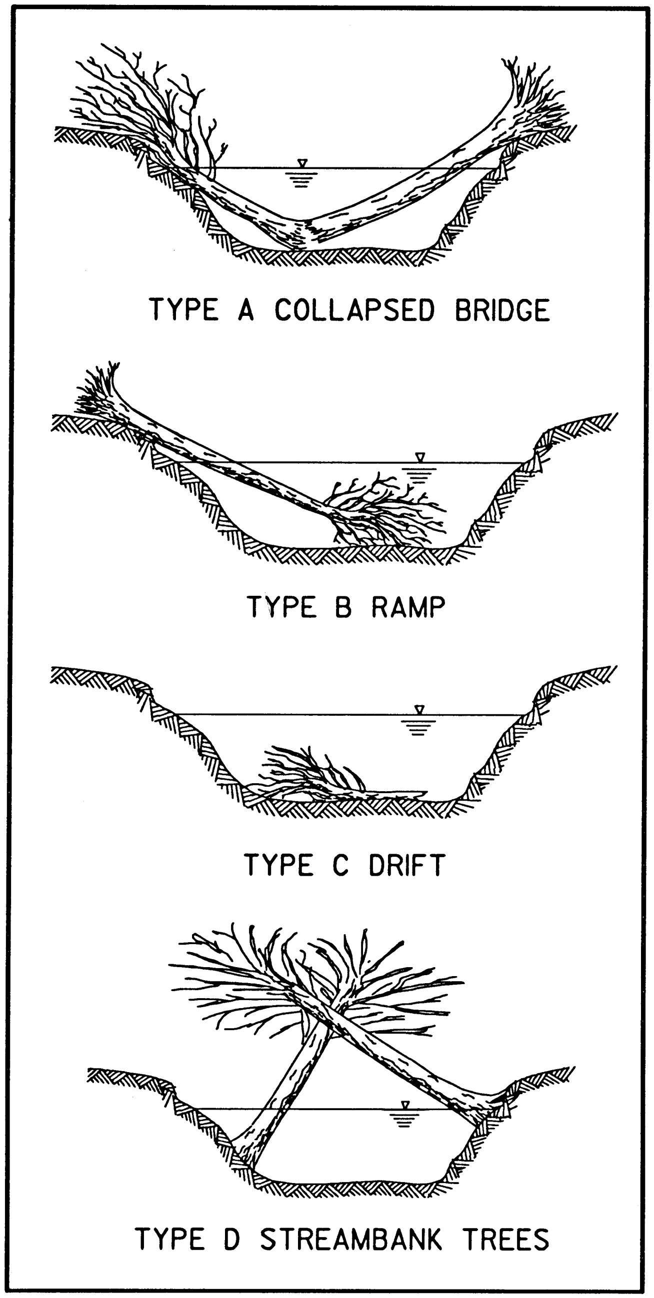

Figure 8. Large woody debris formation types

d. <u>Type D - Streambank trees.</u> Leaning tree(s) (both live and dead) with stable root systems in the side of the bank(s) and with some portion of the roots, trunk, or limbs submerged in water and obstructing the "within-bank" flow.

The approximate size of each LWD formation was visually determined with respect to the average water surface width (Figure 9):

Length:	Width:
$L < B/2$	$W < B/4$
$B/2 \le L \le B$	$B/4 \le W \le B/2$
$L > B$	$B/2 < W \le B$

where

L = Formation length in streamwise direction

B = Mean water surface width at a specific flow

W = Formation width perpendicular to flow direction

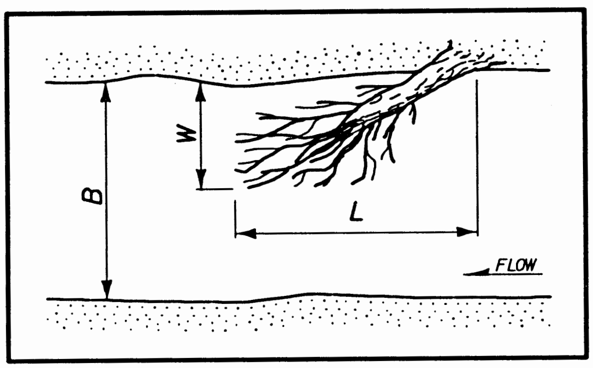

Figure 9. Estimation of LWD formation dimensions

Dye tests

Discharge and associated channel hydraulic parameters were measured using dilution gaging methods. 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 (Figures 10 and 11). Dosage requirements, preparation of the dye standards, and procedures for calibration of the fluorometer were determined using the techniques discussed by Johnson (1984). Dilution gaging tests were conducted at the downstream reach first and then proceeded upstream. Temporary staff gages were established at the upstream and downstream ends of each reach. Gage datums were determined by surveying

Figure 10. Fluorometer equipment

Figure 11. Line with fluorometer attached at downstream end of Reach 2

from previously established benchmarks. During each dye test, water surface elevations were recorded using the temporary staff gages; water surface top widths were measured at five to twelve regularly spaced cross sections.

Physical habitat

Six to ten transects, spaced approximately one channel width apart, were established in each of the three selected reaches at locations judged to be typical of the entire reach. Velocity, depth, substrate (surficial bed material), and cover were measured or classified at intervals along each transect using a tagline to locate sampling points (Figure 12). Depths were determined using wading rods and sounding lines, while velocities were measured at 0.6 depth using Price and Marsh-McBirney current meters. Bed material and cover were visually categorized in the field. Bed types were (a) clay-silt, (b) sand, (c) gravel, (d) leaf litter, and (e) vegetation. Samples of bed material were also collected at each transect for laboratory sieve analyses. Cover type were (a) none, (b) small logs, (c) logjams, (d) rootwads/undercut banks, and (e) canopy.

Figure 12. Measurement of physical habitat characteristics along transect. Ribbons are set on a tagline at 3-ft intervals. Ropes from bow of boat to bank were used to maneuver boat and hold it on station

Data Analysis

LWD density

An approach similar to that provided by Petryk and Bosmajian (1975) was used to calculate LWD density. A form (Appendix C) was developed for purposes of classifying and counting LWD formations. Two different LWD density parameters were computed for each reach. The first parameter DA is the accumulated cross-sectional area ΣA_i of all LWD formations in the reach divided by the reach channel water volume and has dimensions of 1/length.

$$DA = \sum_{i=1}^{n} \frac{A_i}{\bar{A}} L_R = (1/L_R) \sum_{j=A}^{D} f_{Bj} \sum_{k=1}^{3} N_{j,k} f_{Wk} \qquad (1)$$

where

- n = total number of LWD formations in the reach
- A_i = area of ith debris formation in the plane perpendicular to flow
- $\bar{A}$ = reach mean flow cross-sectional area
- L_R = reach length
- f_{Bj} = formation type weighting factor for jth formation type (Table 1)
- $N_{j,k}$ = number of type j LWD formations in kth width category. (See Figure 8 and Appendix C for formation types and Figure 9 and Table 1 for width categories.)
- f_{Wk} = weighting factor based on LWD formation width category

The formation type weighting factor f_{Bj} was assigned to each formation type (Figure 8 and Table 1, top part) prior to data analysis based on the amount of flow typically passing through each formation type and ranged from 0.70 to 1.00. The width weighting factor f_{Wk} is simply the fraction of the flow cross-sectional area occupied by a particular LWD formation. Table 1 (middle part) shows the three width weighting factors used.

The second parameter DV is the dimensionless LWD density. It is the ratio of LWD volume in the reach divided by the reach channel water volume, as follows:

Table 1

Weighting Factors for Computation of LWD Density

For Computation of DA

LWD Formation Type, j	Formation Type Weighting Factor f_{Bj}
A - Collapsed Bridge	0.80
B - Ramp	0.70
C - Drift	0.90
D - Streambank Trees	1.00/0.707 $\bar{D}$*

LWD Formation Width Category, k	Width Size Range	Width Weighting Factor f_{wk}
1	$W < B/4$**	0.125
2	$B/4 \leq W \leq B/2$	0.375
3	$B/2 < W \leq B$	0.750

For Computation of DV

LWD Formation Size Category, k	Length† Size Range	Width Size Range	Size Weighting Factor f_{si}
1	$L < B/2$	$W \leq B/4$	0.0313
2	$L < B/2$	$B/4 < W \leq B/2$	0.0938
3	$L < B/2$	$B/2 < W \leq B$	0.1875
4	$B/2 \leq L < B$	$W \leq B/4$	0.0938
5	$B/2 \leq L < B$	$B/4 < W \leq B/2$	0.2813
6	$B/2 \leq L < B$	$B/2 < W \leq B$	0.5625
7	$L > B$	$W \leq B/4$	0.1250
8	$L > B$	$B/4 < W \leq B/2$	0.3750
9	$L > B$	$B/2 < W \leq B$	0.3750

* $\bar{D}$ = reach mean depth, ft.
** W = the maximum dimension of a given LWD formation in the direction perpendicular to flow. B = reach mean width, ft.
† L = the maximum dimension of a given LWD formation in the direction parallel to the flow.

$$DV = \sum_{i=1}^{n} \frac{A_i\ L_i}{\overline{A}\ L_R} = (\overline{B}/L_R) \sum_{j=A}^{D} f_{Bj} \sum_{k=1}^{9} M_{j,k}\ f_{Si} \tag{2}$$

where

L_i = dimensions of the ith LWD formation in direction parallel to flow for the kth size category

$\overline{B}$ = reach mean water surface width

$M_{j,k}$ = number of type j LWD formations in kth size category (see lower part of Table 1 for size categories)

f_{Si} = size weighting factor

The size weighting factor f_{Si} was based on LWD size category (shown in lower part of Table 1). This factor is the product of the midpoints of the length and width categories shown in Table 1. For example, an LWD formation with a length in the category $(B/2 < L < B)$ and with a width in the category $W < B/4$ would have a weighting factor equal to 0.75 x 0.125 = 0.0938.

In addition to completing the form in Appendix C for each studied flow condition in each study reach, LWD density was quantified using two additional techniques. At low flow, the number and diameter of streambank trees was determined for two subreaches, each about 430 ft long. The number and diameter of all woody debris stems breaking the water surface at low flow was determined for each study reach.

Dye tests

The dye tracer tests yielded curves of dye concentration versus time. A computer program called DYECON (Schroeder and Palermo 1990) was used to calculate reach mean hydraulic parameters and dispersion coefficients. The time of travel was defined as the time elapsed between dye release and the passage of the dye cloud centroid at the downstream end of the reach. The mean velocity $\bar{V}$ was calculated as

$$\overline{V} = \frac{Reach\ Length}{Time\ of\ Travel} = \frac{L_R}{\overline{t}} \tag{3}$$

The discharge Q was calculated as (Richards 1982):

$$Q = \frac{K\ (C_i - C_b)\ V_o}{\int_{t=o}^{\infty} (C_d - C_b)\ dt} \tag{4}$$

where

Q = discharge, cfs

K = 5.886 x 10^5 (conversion factor to change ℓ/min to cfs)

C_i = concentration of dye solution injected

C_b = background concentration in the stream

V_o = volume of dye injected at upstream end of reach, ℓ

C_d = concentration measured at downstream end of reach at time t

t = time, min

The integral in the denominator is equal to the area under the dye curve. The reach mean cross-sectional area was calculated as

$$\overline{A} = \frac{Q}{\overline{V}} \tag{5}$$

The mean water surface width B was determined as the average of five to twelve measurements made at regular intervals along the reach during the dye test. The mean hydraulic depth and hydraulic radius were then calculated as

$$\overline{D} = \overline{R} = \frac{\overline{A}}{\overline{B}} \tag{6}$$

Water surface elevations were calculated for both the upstream E_u and downstream E_d ends of the reach by reading the stage gages and adjusting readings to the surveyed datums. The water surface slope was then determined by dividing the elevation difference by the reach length L_R .

$$S_w = \frac{E_u - E_d}{L_R} \tag{7}$$

The reach resistance factor, Darcy-Weisbach f , was then calculated as

$$f = \frac{8gRS_w}{\overline{V}^2} \tag{8}$$

where g = acceleration of gravity (32.17 ft/sec^2).

Heterogeneity of flow conditions and gross longitudinal mixing was determined from dye curves in four ways. Because the dye curve represents a frequency distribution of travel times,* it was used to compute travel time variance σ_t^2. The dispersion variance index DI is a dimensionless number that measures the amount of mixing occurring and is calculated from the dye curve data as

$$DI = \frac{\sigma_t^2}{\overline{t}^2} \tag{9}$$

where $\overline{t}$ = mean travel time.

The Morrill Index is another dimensionless measure of longitudinal mixing and variability of flow conditions. It is the ratio T_{90}/T_{10} where T_{90} is the time required for 90 percent of the dye to exit the reach and T_{10} is the time required for 10 percent of the dye to exit. Higher values of the Morrill Index indicate a wider spread in the base of the dye curve and more variable conditions.

The longitudinal dispersion coefficient D_L was determined using a method provided by Fischer (1968).

$$D_L = \overline{V}^2 \frac{\sigma_t^2}{2\overline{t}} \tag{10}$$

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* In an instantaneous slug injection dye test, a parcel of water is stained with dye at the upstream end of the reach. As the parcel moves through the reach and mixes with adjacent parcels, some of the subparcels of dye-stained water move rapidly; some move more slowly. The dye curves provide an indication of the frequency distribution of subparcel travel times. The normalized dye curve is a frequency distribution for velocities.

The expression proposed by Liu and Cheng (1980) for prediction of the longitudinal dispersion coefficient was also used to compute values for comparison with measured values.

$$D_{LP} = 0.5 \frac{u_* \overline{A}^2}{\overline{D}^3} \tag{11}$$

where the shear velocity u_* was computed as

$$u_* = (g\overline{R}S_w)^{1/2} \tag{12}$$

Physical habitat

Frequency histograms were generated for each physical habitat variable (velocity, depth, bed type, and cover) and each reach. Means and standard deviations of depth and velocity and for median bed material size were computed for each reach. Analysis of variance (ANOVA) was performed for depth, velocity, and bed material size data grouped by reach and grouped into sampling points with cover and without cover.

Shannon diversity indices (Magurran 1988) based on depth, velocity, and bed type were calculated for each of the three subreaches (Gorman and Karr 1978). First, a composite integer score was assigned to each grid point where physical habitat data were collected. Composite integer scores for each point were developed as follows:

Composite integer score = (100 x depth score) + (10 x velocity score) + (1 x bed type score) (13)

Component scores for depth, velocity, and bed type were assigned based on the following scheme:

Score	Depth ft	Velocity fps	Bed type
1	0-0.16	0-0.03	clay/silt
2	0.17-0.66	0.04-0.16	sand
3	0.67-1.64	0.17-0.66	gravel
4	1.65-2.62	0.66-1.31	leaf litter
5	2.62 or greater	1.32 or greater	vegetation

Additional scores were computed for each grid point using the above formula, but omitting bed type. There were 125 possible values (i.e., 5 x 5 x 5) for composite scores based on all three variables but only 25 possible scores based on depth and velocity. Next, the frequency distribution of composite scores was determined for each subreach. Finally, Shannon indices H' were computed for each subreach using the formula

$$H' = -\sum p_i \ln (p_i) \qquad (14)$$

where p_i is the proportion of composite integer scores in the ith category. Each unique integer score constituted a category. For a perfectly uniform reach (i.e., depth, velocity, and bed type are the same at all transect points), $H' = 0$ because $i = 1$ and $p_i = 1$. Diverse streams normally yield H' values between 3 and 4 (Gorman and Karr 1978).

Effects of LWD on
hydraulic resistance

Petryk and Bosmajian (1975) developed a procedure for predicting Manning's n for vegetated channels as a function of flow depth and vegetation characteristics. This procedure is applicable to open channels where vegetation plays a major role in the flow resistance, such as flows across broad, heavily vegetated floodplains, roadside drainage ditches with thick, tall vegetation, and canals choked with aquatic vegetation. The equation, which was developed by assuming that flow conditions are uniform and that the approach velocity to each plant stem is equal to the mean velocity, contains a term referred to as "vegetation density."

By applying similar reasoning to uniform steady flow through a straight channel reach where LWD plays a major role in flow resistance, total resistance can be expressed as

$$f_t = f_b + f_d \tag{15}$$

where

f_t = total Darcy-Weisbach friction factor

f_b = boundary friction factor excluding LWD effects

f_d = friction factor due to LWD

Total head loss is the sum of a boundary friction loss and a LWD blockage loss, as follows:

$$h_L = S_E\, L = \frac{[(f_b L/4\bar{R}) + K_d]\bar{V}^2}{2g} \tag{16}$$

where

h_L = total head loss, ft

S_E = slope of the energy gradient, ft/ft

L = reach length, ft

$\bar{R}$ = hydraulic radius, ft

K_d = dimensionless loss coefficient (dependent upon LWD density)

The energy slope can be calculated using a total friction factor from the Darcy-Weisbach equation, as follows:

$$S_E = \frac{f_t \bar{V}^2}{(8g\bar{R})} \tag{17}$$

Substituting this expression for S_E into Equation 16 gives

$$f_t = f_b + \frac{4\bar{R}K_d}{L} \tag{18}$$

Therefore,

$$f_d = \frac{4\bar{R}K_d}{L} \tag{19}$$

The ratio K_d/L may be expressed in terms of LWD density as:

$$\frac{K_d}{L} = DA \tag{20}$$

The boundary friction factor f_b can be estimated using a variety of methods. Miller and Wenzel (1985) compared observed versus predicted values of f_b for low flow in alluvial channels with values predicted using several approaches and concluded that the Kennedy-Alam-Lovera curves (Alam and Kennedy 1969, Lovera and Kennedy 1969) yielded the lowest standard error of estimate and highest positive correlation coefficient. They noted, however, at the riffle sections the Kennedy curves may become ineffective if used for low-flow conditions in streams with pool-riffle sequences. They concluded that under low-flow conditions, the total energy loss should include an additional term for local or eddy losses due to abrupt expansions and contractions. They also noted that as the discharge increased, the local losses became less significant in accurately predicting the flow characteristics.

Values of f_b were calculated using the Kennedy curves and the hydraulic parameters determined from the dye tests and the median bed grain size determined from the sieve analyses. Values for f_d were then calculated using Equations 1, 19, and 20. Computed values of $f_t = f_b + f_d$ were compared with values measured using dye tests (Equation 8).

PART III: RESULTS

LWD surveys and dye tests performed during this study resulted in a total of 22 data sets. Dates of surveys and tests and associated stages are shown in Table 2. Stages ranged from extremely low to near bankfull (Figure 13). Day-to-day variations in stage were slight (generally less than 0.5 ft) because of the presence of an extremely large log jam upstream from the study reach that ponded water onto the floodplain.

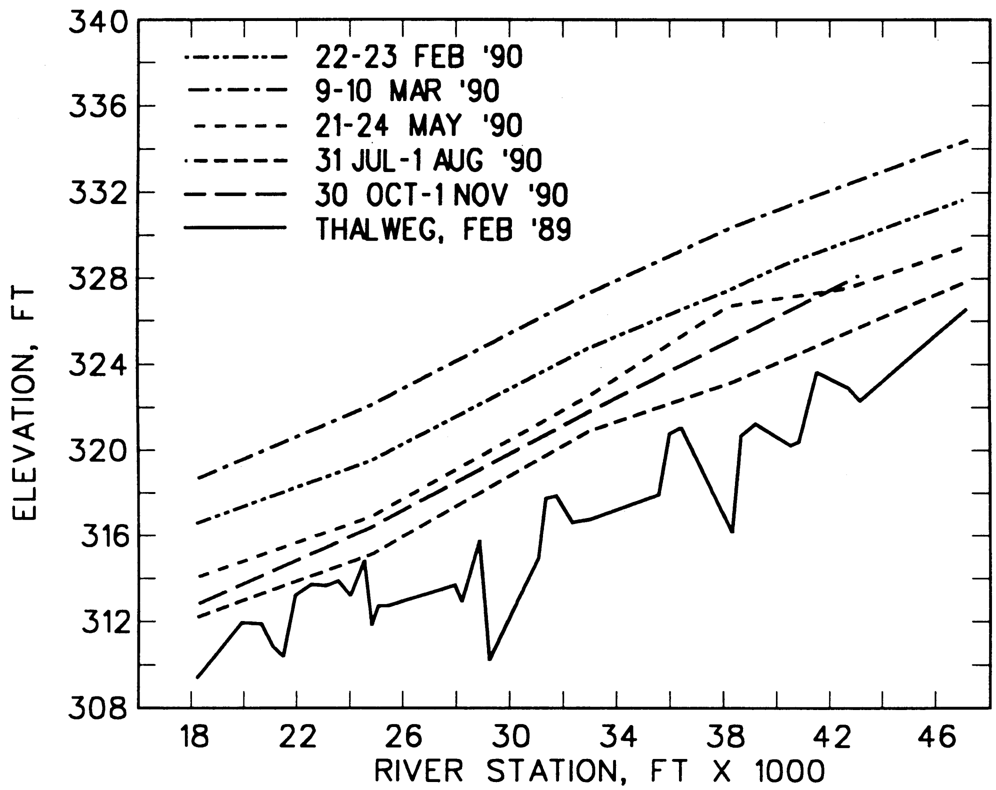


Figure 13. Water surface profile for study reach during dye tests and LWD density counts

LWD Density

Results of the LWD surveys and calculated densities are shown in Table 3 and summarized in Table 4. Density of LWD was assumed to be negligible in fall 1989 in the lower reach because this material had been removed only a few weeks prior to initiation of the study.

Nine LWD surveys were performed on the upper and middle reaches prior to LWD removal (Tables 3 and 4). Large woody debris densities DA ranged from

Table 2

Field Study Dates and Water Surface Slopes

Field Study Number	Reach and Condition*	LWD Survey Date	Dye Study Date	Water Surface Elevations: LWD Survey: Upper Gage ft	LWD Survey: Lower Gage ft	Dye Study: Upper Gage ft	Dye Study: Lower Gage ft	Reach Length ft	Water Surface Slope ft/mile
1	1-C	--	10/30/90	--	--	316.32	312.72	6629	2.87
2	1-C	02/22/90	02/22/90	319.51	316.48	319.51	316.48	6629	2.41
3	1-C	03/09/90	03/09/90	--	--	321.96	318.52	6629	2.74
4	1-C	--	03/10/90	--	--	322.34	318.79	6629	2.83
5	1-C	05/21/90	05/21/90	316.82	314.03	316.82	314.03	6629	2.22
7	2-U	--	10/30/89	--	--	325.08	321.88	5245	3.22
8	2-U	12/06/89	--	325.16	321.65	--	--	5245	3.53
9	2-U	02/23/90	02/23/90	327.51	324.82	327.51	324.82	5245	2.71
10	2-U	--	03/09/90	--	--	330.36	327.23	5245	3.15
11	2-U	03/10/90	03/10/90	--	--	330.49	327.38	5245	3.13
12	2-U	05/11/90	--	326.83	322.73	--	--	5280	4.10
13	2-U	5/22/90	05/22/90	326.64	322.54	326.64	322.54	5280	4.10
14	2-C	07/31/90	07/31/90	323.17	320.96	323.17	320.96	5300	2.21
15	3-U	--	11/01/89	--	--	328.16	325.08	4918	3.31
16	3-U	12/06/89	--	328.38	325.16	--	--	4918	3.46
17	3-U	02/23/90	02/23/90	331.76	328.80	331.76	328.80	6629	2.36
18	3-U	03/09/90	03/09/90	--	--	334.39	331.37	6629	2.41
19	3-U	--	03/10/90	--	--	334.75	331.52	6629	2.57
20	3-U	05/11/90	--	330.22	327.08	--	--	6629	2.50
21	3-C	05/24/90	05/24/90	329.49	327.55	329.49	327.55	4370	2.34
22	3-C	08/01/90	08/01/90	327.84	324.32	327.84	324.32	6629	2.82

* Reach: 1 = lower, 2 = middle, 3 = upper.
Condition: C = cleared, U = uncleared.

Table 3

LWD Counts and Density

Field Study Number	Reach and Condition*	Number of Formations**				LWD Density	
		A	B	C	D	DA (10^{-5} ft^{-1})	DV (10^{-4})
2	1-C	0	8	4	55	38	62
3	1-C	0	8	4	96	37	70
5	1-C	4	33	8	96	110	222
8	2-U	5	37	26	18	299	754
9	2-U	8	51	8	97	231	316
11	2-U	8	51	8	175	264	327
12	2-U	11	58	6	110	371	818
13	2-U	12	70	11	110	382	669
14	2-C	6	70	17	38	251	371
16	3-U	7	32	18	16	300	869
17	3-U	7	52	12	123	177	346
18	3-U	7	52	12	130	179	354
20	3-U	10	15	51	70	260	456
21	3-C	4	22	16	46	149	217
22	3-C	17	63	26	77	280	405

* Reach: 1 = lower, 2 = middle, 3 = upper.
Condition: C = cleared, U = uncleared.

** Formation types: A = collapsed bridge, B = ramp, C = drift, D = streambank trees.

Table 4

Effects of Selective LWD Removal on LWD Density

LWD Density Measure	Uncleared Reaches Number	Uncleared Reaches Mean	Cleared Reaches Number	Cleared Reaches Mean	Percent Difference in Means
DA, 10^{-5} ft^{-1}	9	274	6	144	-47
DV, 10^{-4}	9	545	6	225	-59
Streambank trees or stumps, no./ft of bank	1	0.29	2	0.27	-7
Diameter of streambank trees or stumps, ft	1	0.90	2	0.84	-7
LWD stems protruding through water surface, no./ft	1	0.18	2	0.032	-82
LWD stem area/water surface area, ft^2/1,000 ft^2	1	1.31	2	0.145	-89

177 to 382 per 10^5 ft and averaged $274/10^5$ ft. Six surveys were performed after LWD removal; densities ranged from 37 to 280 per 10^5 ft and averaged $144/10^5$ ft. Dimensionless LWD densities DV averaged 545×10^{-4} for uncleared reaches and 225×10^{-4} for cleared reaches. Density values for the upper and middle reach after clearing were higher than for the lower reach after clearing, primarily because of drift formations (Figure 8) exposed by bed scour following construction. Variation of LWD density DA with discharge and mean hydraulic depth is shown in Figure 14. In general, LWD density decreased as stages increased from low- to mid-bank elevation but remained relatively constant from mid bank to near bank full. However, LWD formations that were submerged deeply enough to be invisible were not counted. Therefore, LWD density may have been underestimated.

Trees growing between the water's edge and top bank in a 490-ft segment of the middle uncleared reach were counted and measured on 24 May 1990. Stem diameters averaged 10.8 in., and lineal density was 0.27 tree/ft or one tree every 3.70 ft. Stumps were also counted in a 426-ft segment of the lower cleared reach during the same period. The mean stump diameter was 10.1 in., with a lineal density of 0.29 stump/ft or one stump every 3.45 ft.

The area of LWD in the plane of the water surface was measured as an additional descriptor of LWD density. All LWD stems having diameters greater than 1.5 in. protruding through the water surface were counted and measured in each study reach during 23-24 May 1990. Results are shown in Table 5.

All of the measures of LWD density computed for this study are summarized in Table 4. Selective removal of LWD on the South Fork Obion River

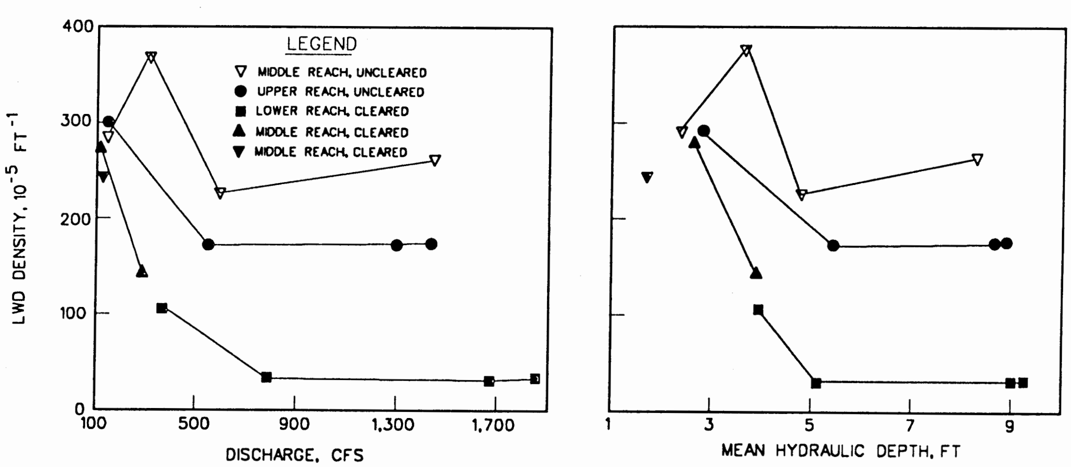


Figure 14. Large woody debris density versus mean discharge and hydraulic depth

Table 5

Cross-Sectional Area of LWD Stems Protruding Through Water Surface

Reach and Condition *	Length ft	Mean Width of Water Surface ft	Water Surface Area acres	Number of Stems Protruding Through Water Surface	Mean Diameter of Stems in Plane of Water Surface ft	Cross-Sectional Area of Stems in Plane of Water Surface ft^2	Ratio of LWD Area to Water Area $x10^3$
1-C	426	48.6	0.48	11	0.46	1.81	0.087
2-U	490	57.6	0.65	86	0.74	37.2	1.3
3-C	4,370	61	6.12	170	0.63	52.1	0.20

* Reach: 1 = lower, 2 = middle, 3 = upper.
Condition: C = cleared, U = uncleared.

resulted in reductions of LWD density ranging from 50 to 90 percent, depending on how LWD density was defined and measured.

Dye Tests

Data reduction

Time-concentration curves from 17 dye tests are shown in Figure 15 and Tables 6-9. These data along with stage measurements (Table 2) were used to compute mean velocity, discharge, mean cross-sectional area, mean hydraulic depth (Table 7), and channel roughness (Table 8) and to make several measures of longitudinal dispersion (Table 9). The raw dye curves consisted of ordered time-concentration pairs. These curves were normalized to eliminate the effects of unequal reach lengths and dye volumes. Times were converted to velocities by dividing them into reach length. Dye concentrations C_i were normalized by dividing by C_v, such that

$$C_v = L_R \sum_{i=1}^{N-1} \left(\frac{C_i + C_{i+1}}{2} \right) \left(\frac{1}{t_{i+1}} - \frac{1}{t_i} \right) \tag{21}$$

where

L_R = reach length, ft

C_i = dye concentration, ppb measured at t_i

t_i = time, min

The dye curves were replotted as normalized dye concentration C_i/C_v versus velocity in feet per second (Figure 16). The normalized curves all enclose areas of unity. Further, they represent frequency distributions of reach mean velocity.

Velocities

The top row of plots in Figure 16 shows results from tests conducted at near-bank-full flow, the middle row shows mid-bank flow results, and the bottom row shows results from low flow. Reach mean velocity increased and became less uniform with discharge. A very small percentage of uncleared reach mean velocities exceeded 3 fps, but more than half of the reach mean velocities in cleared reaches at flows of 650 cfs or more exceeded 3 fps.

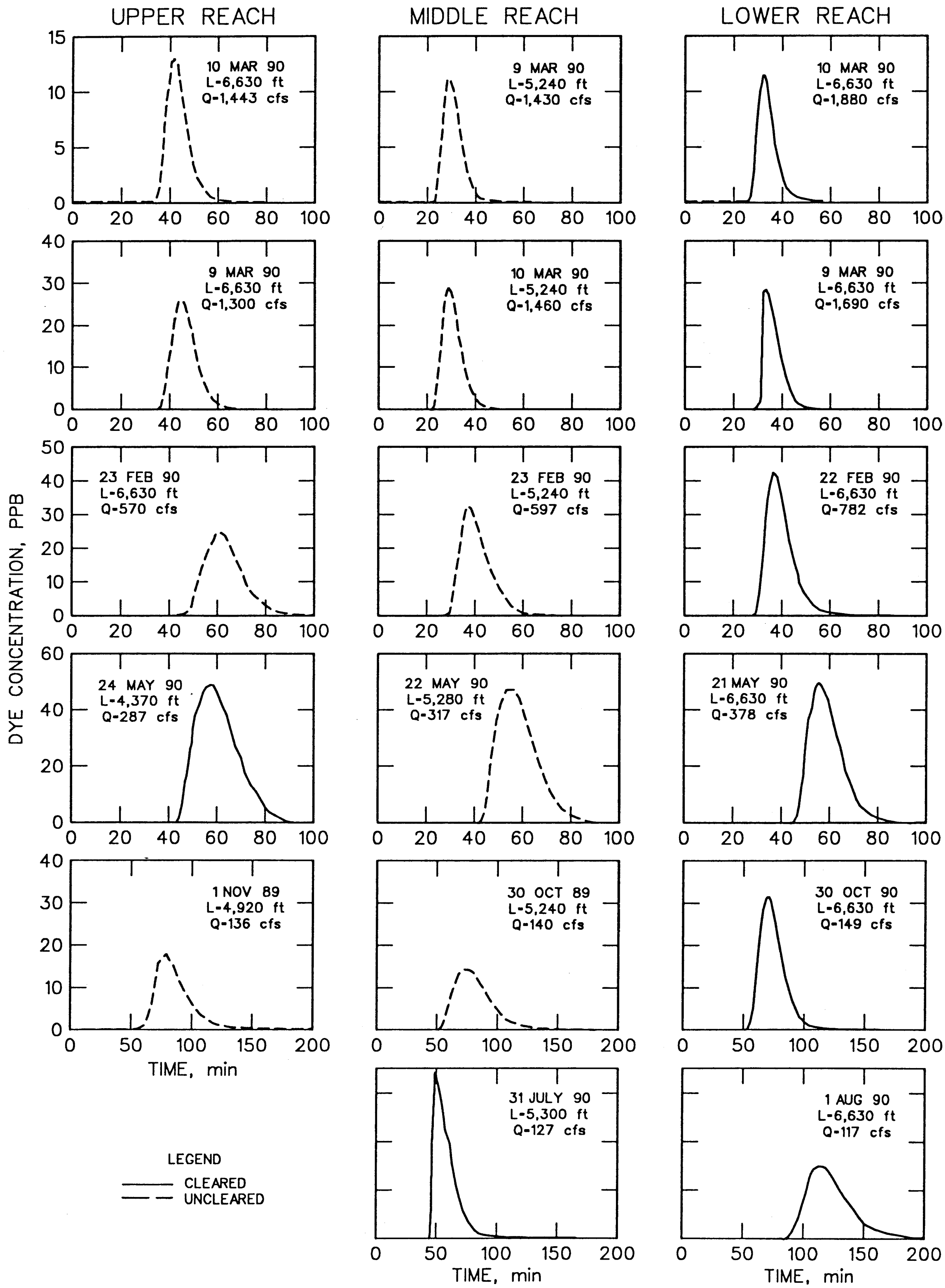


Figure 15. Dye curves

Table 6

Dye Test Results

Field Study Number	Reach and Condition*	Type of Dye	Volume of Dye ℓ	Average Temperature, °C		Concentration			Time Parameter, min						
									Mean Retention Time	Modal Time	Latest Time >10% Max. Concentration	Time to Reach Percentage of Dye Curve Area			
				Standards	River	Background ppb	Mean ppb	Maximum ppb				$T_0\%$	$T_{10}\%$	$T_{50}\%$	$T_{90}\%$
1	1-C	WT	0.75	≈20.00	≈20.00	0.14	10.93	31.36	74.4	69.0	95.8	53.5	62.9	72.7	87.9
2	1-C	WT	3.00	≈22.22	12.80	0.14	14.77	42.39	40.0	37.1	51.7	28.5	33.8	39.0	47.1
3	1-C	WT	3.00	≈22.22	12.10	0.01	10.06	28.87	36.9	33.5	45.2	29.1	32.5	35.9	42.3
4	1-C	B	2.25	≈22.22	13.20	0.09	2.62	7.62	34.4	32.5	43.1	26.4	29.9	33.7	39.7
5	1-C	WT	0.50	25.50	21.50	0.00	17.13	49.37	59.3	56.0	75.0	45.5	51.2	58.2	68.7
7	2-U	WT	0.50	≈20.00	≈20.00	0.05	4.99	14.45	82.0	72.0	116.4	52.0	64.1	79.1	103.3
9	2-U	WT	2.00	≈22.22	11.00	0.07	11.38	32.56	41.1	37.1	54.4	29.1	34.2	40.1	49.3
10	2-U	B	3.00	≈22.22	12.20	0.08	3.85	11.09	31.0	29.3	39.9	22.8	26.5	30.4	36.4
11	2-U	WT	3.00	≈22.22	13.75	0.07	10.25	29.19	30.9	28.9	40.0	22.6	26.3	30.3	36.4
13	2-U	WT	0.50	21.00	19.00	0.00	17.02	47.37	58.6	53.5	77.6	42.5	49.1	57.6	69.7
14	2-C	WT	0.25	31.00	26.50	0.00	22.11	68.20	58.3	50.0	76.6	44.5	48.5	56.0	70.8
15	3-U	WT	0.50	≈20.00	≈20.00	0.34	5.99	17.66	86.9	78.0	115.0	58.0	70.7	83.7	105.4
17	3-U	WT	2.00	≈22.22	10.40	0.04	8.74	25.63	63.6	60.9	80.6	46.0	54.1	62.4	74.2
18	3-U	WT	3.00	≈22.22	12.45	0.08	9.10	25.90	47.1	45.5	58.1	35.4	41.2	46.4	53.9
19	3-U	B	3.00	≈22.22	14.80	0.08	4.49	12.97	43.7	42.0	53.9	33.6	38.3	43.0	49.9
21	3-C	WT	0.50	23.00	19.75	0.00	17.68	49.88	60.9	56.5	80.3	44.0	50.8	59.7	72.5
22	3-C	WT	0.25	28.25	25.00	0.05	12.99	115.95	123.6	116.0	141.1	84.0	102.2	118.1	148.0

* Reach: 1 = lower, 2 = middle, 3 = upper.
Condition: C = cleared, U = uncleared.

Table 7

Dye Test Conditions

Field Study Number	Reach and Condition*	Reach Length ft	Water Surface Slope ft/mile	Discharge cfs	Mean Velocity fps	Mean Water Surface Top Width ft	Mean Flow Area ft^2	Mean Hydraulic Depth ft
1	1-C	6,629	2.87	149	1.49	47.6	100	2.1
2	1-C	6,629	2.41	782	2.76	55.6	283	5.1
3	1-C	6,629	2.74	1,691	3.00	62.6	564	9.0
4	1-C	6,629	2.83	1,877	3.21	62.9	585	9.3
5	1-C	6,629	2.22	378	1.87	52.0	202	3.9
7	2-U	5,245	3.22	140	1.06	55.0	132	2.4
9	2-U	5,245	2.71	597	2.13	60.3	280	4.6
10	2-U	5,245	3.15	1,430	2.82	62.0	507	8.2
11	2-U	5,245	3.13	1,457	2.83	62.0	515	8.3
13	2-U	5,280	4.10	317	1.50	57.1	211	3.7
14	2-C	5,300	2.21	127	1.52	49.4	84	1.7
15	3-U	4,918	3.31	136	0.95	51.0	143	2.8
17	3-U	6,629	2.36	570	1.74	62.2	328	5.3
18	3-U	6,629	2.41	1,301	2.35	63.6	554	8.7
19	3-U	6,629	2.57	1,443	2.53	64.0	570	8.9
21	3-C	4,370	2.34	287	1.20	61.0	239	3.9
22	3-C	6,629	2.82	117	0.89	47.0	131	2.8

* Reach: 1 = lower, 2 = middle, 3 = upper.
Condition: C = cleared, U = uncleared.

Table 8

Measured and Computed Friction Factors

Field Study Number	Reach and Condition*	Measured Manning's n	Measured Darcy f	Computed Using Kennedy Curves: Boundary f_b	Debris f_d	Total $f_t = f_b + f_d$	Differences $f - f_b$	Differences $f - f_t$
1	1-C	0.038	0.132	0.162	0.000	0.162	-0.030	-0.030
2	1-C	0.034	0.079	0.085	0.007	0.092	-0.006	-0.013
3	1-C	0.049	0.134	0.074	0.013	0.087	0.060	0.047
4	1-C	0.048	0.124	0.075	0.013	0.088	0.049	0.036
5	1-C	0.041	0.121	0.121	0.017	0.138	0.000	-0.017
7	2-U	0.062	0.329	0.167	0.028	0.195	0.162	0.134
9	2-U	0.045	0.137	0.092	0.043	0.135	0.045	0.002
10	2-U	0.053	0.158	0.067	0.086	0.153	0.091	0.005
11	2-U	0.053	0.158	0.067	0.087	0.154	0.091	0.004
13	2-U	0.066	0.329	0.120	0.056	0.176	0.209	0.153
14	2-C	0.029	0.079	0.137	0.017	0.154	-0.058	-0.075
15	3-U	0.079	0.512	0.160	0.032	0.192	0.352	0.320
17	3-U	0.055	0.202	0.085	0.037	0.122	0.117	0.080
18	3-U	0.058	0.185	0.064	0.061	0.125	0.121	0.064
19	3-U	0.056	0.175	0.058	0.063	0.121	0.117	0.058
21	3-C	0.065	0.311	0.120	0.022	0.142	0.191	0.169
22	3-C	0.077	0.486	0.169	0.031	0.200	0.317	0.286

* Reach: 1 = lower, 2 = middle, 3 = upper.
Condition: C = cleared, U = uncleared.

Table 9

Dye Curve Dispersion

Study No.	Time of Travel Variance min^2	Dispersion Index	Longitudinal Dispersion Coefficients Measured ft^2/sec	Computed ft^2/sec	Morrill Index T_{90}/T_{10}
1	109	0.020	97	104	1.40
2	34	0.021	193	83	1.39
3	20	0.015	149	85	1.30
4	16	0.014	145	85	1.33
5	48	0.014	85	79	1.34
7	264	0.039	110	134	1.61
9	37	0.022	122	105	1.44
10	16	0.017	125	93	1.37
11	17	0.017	129	92	1.39
13	66	0.019	76	134	1.42
14	98	0.029	116	109	1.46
15	281	0.037	86	113	1.49
17	75	0.019	108	100	1.37
18	26	0.012	90	83	1.31
19	22	0.012	98	85	1.30
Correlation r with time of travel variance	1.00	0.91*	-0.35	0.68*	0.82*

* Significant at $p = 0.05$.

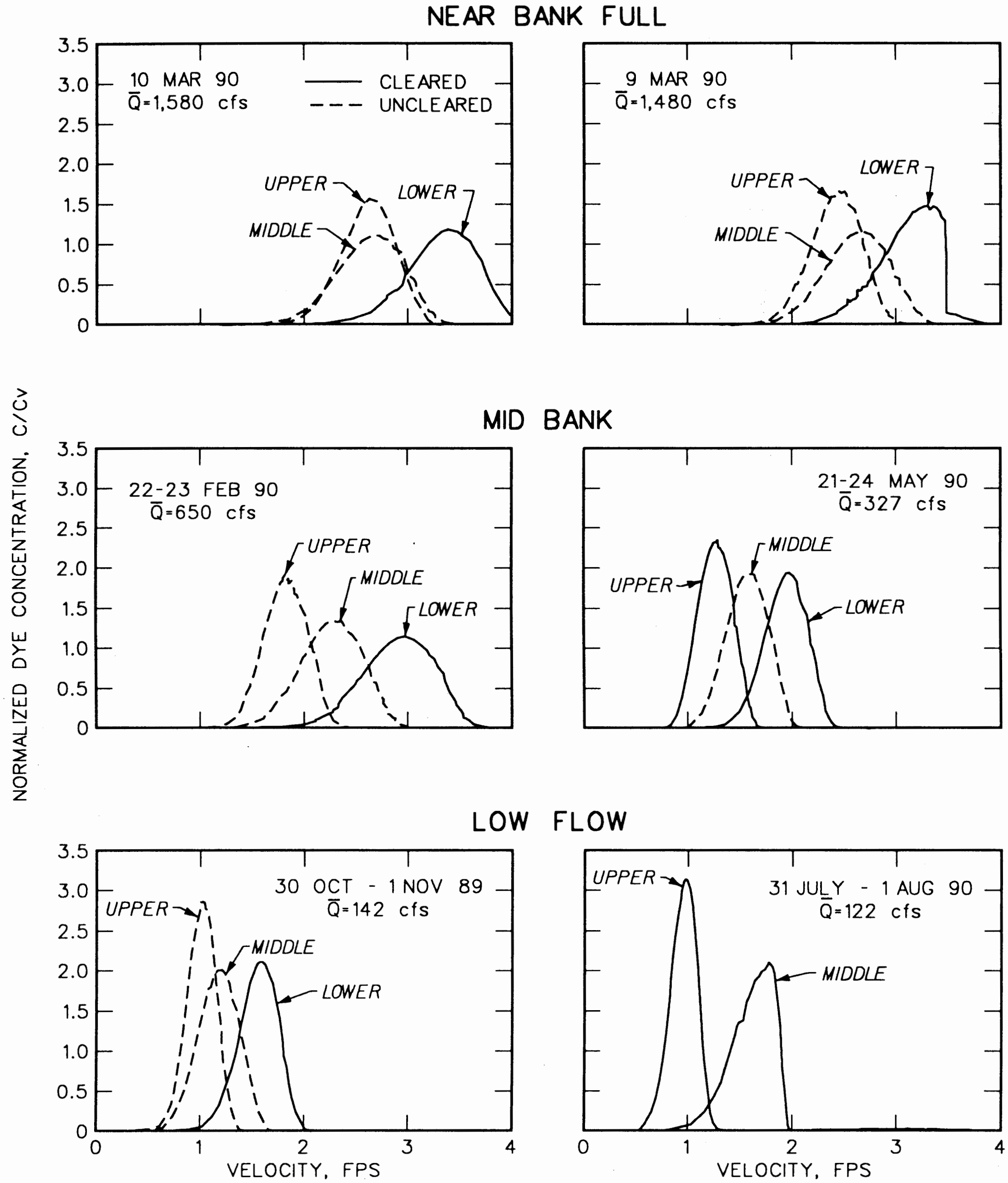


Figure 16. Normalized dye concentration versus reach mean velocity

For a given stage, slopes were greater for uncleared reaches. Mean velocities were always less for uncleared reaches with the exception of the upper reach at mid-bank flow (Test 21, 24 May 1990, Q = 287 cfs). Velocity in the upper reach may have been depressed because of backwater effects of the uncleared middle reach. The curve for the upper reach at extreme low flow (Test 22, 1 August 1990, Q = 117 cfs) also appears to indicate extremely low velocities even though the reach was cleared prior to the test. Stages were so low during this test that emergent bars appeared and meandering flow occurred. Due to these anomalies, the data resulting from Tests 21 and 22 were excluded from further analysis.

Measured friction factors

Measured Darcy-Weisbach friction factors ranged from 0.079 to 0.512 (Table 8) and were smaller for higher discharges (Figure 17). Corresponding Manning's n values ranged between 0.034 and 0.079. The LWD effects on channel roughness were most pronounced at low flow. Evidently LWD exerted less influence on high flows as it became more deeply submerged. Friction factors for cleared and uncleared reaches converged at higher flows (Figure 17). At higher flows (>350 cfs), mean values of f for cleared (n = 4, mean = 0.11) and uncleared (n = 6, mean = 0.17) reaches were close but significantly different at a confidence level of 99.93 percent (probability of t = 0.0007). Corresponding mean Manning's n values were 0.043 for cleared reaches and 0.053 for uncleared reaches.

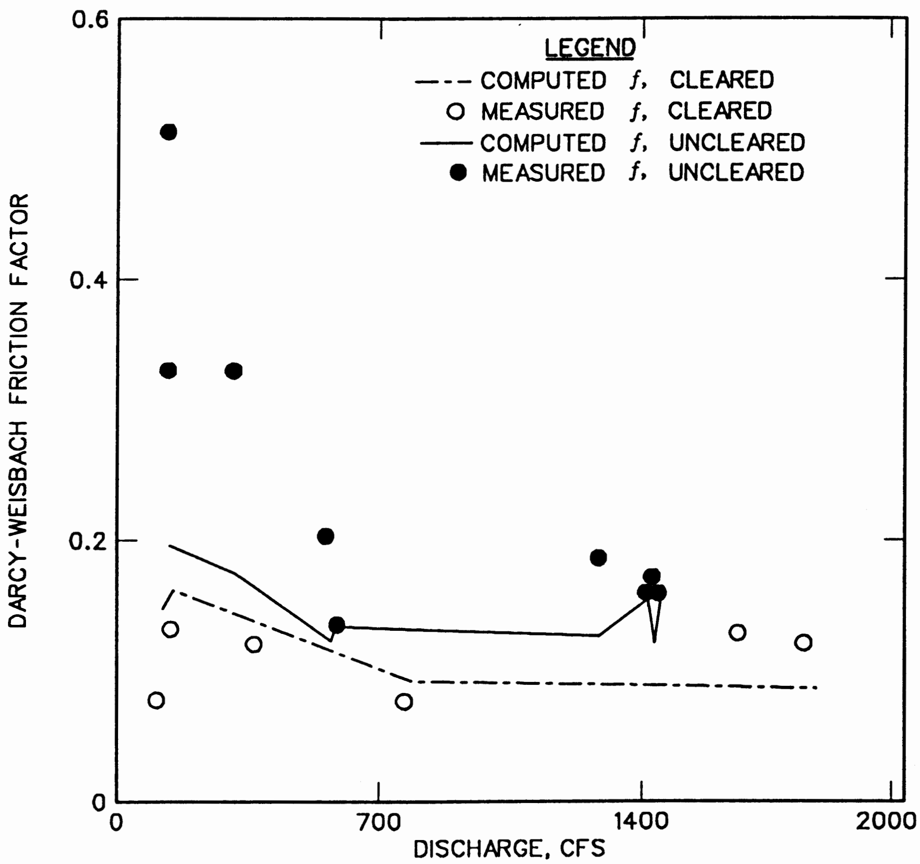


Figure 17. Measured and computed Darcy-Weisbach friction factors versus discharge. Note: the computed curves are based on the Kennedy procedure

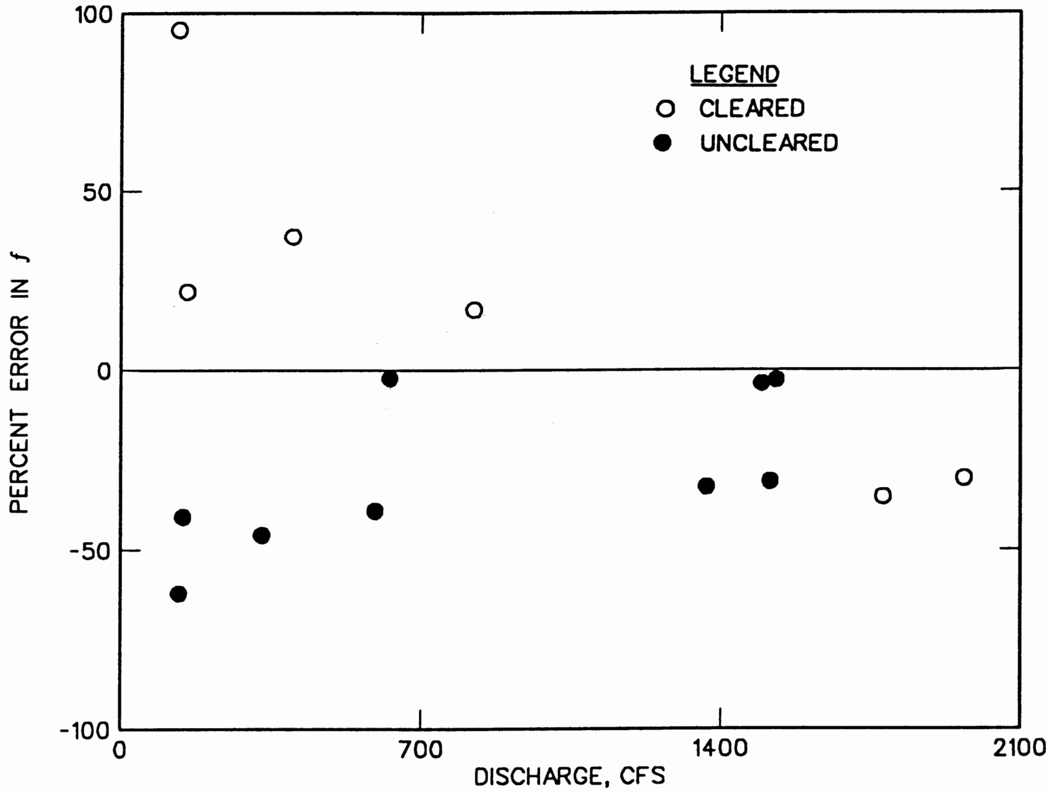
Computed friction factors

Computed Darcy-Weisbach friction factors ranged from 0.092 to 0.200 (Table 10). Flat bed (grain) resistance was generally less than 10 percent of the total computed f , while resistance due to bedforms ranged from about 30 to 80 percent of the total, and resistance due to LWD varied from about 10 to 60 percent of the total. Computed values of f differed from measured values by -62 to +95 percent, and were always less than measured values for uncleared reaches. Computed friction factors were most accurate for near-bank-full stage conditions (errors ranged from -3 to -35 percent (Figure 18). Computed values were closer to measured values for cleared reaches (SD of errors = 0.022) than for uncleared reaches (SD of errors = 0.102). Errors were larger for 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).

Table 10

Physical Habitat Summary Statistics

Descriptor	Mean [SD] Depth ft	Velocity fps	D_{50} mm
30 October-1 November 1989			
Cleared lower reach	2.76 [0.56]	1.29 [0.47]	0.59 [0.18]
Uncleared middle reach	2.68 [1.18]	1.06 [0.67]	0.44 [0.16]
Uncleared upper reach	3.04 [1.20]	0.85 [0.43]	0.27 [0.11]
Points without cover	3.08 [0.88]	1.28 [0.42]	0.47 [0.19]
Points with cover	2.39 [1.16]	0.69 [0.58]	0.31 [0.20]
21-24 May 1990			
Cleared lower reach	4.37 [0.86]	1.62 [0.71]	0.57 [0.08]
Uncleared middle reach	3.34 [1.11]	1.23 [0.79]	0.44 [0.18]
Points without cover	3.89 [1.05]	1.45 [1.10]	0.50 [0.12]
Points with cover	2.74 [1.10]	0.92 [0.71]	0.32 [0.04]



Note: Percent error = $\frac{f \text{ computed} - f \text{ measured}}{f \text{ measured}}$

Figure 18. Percent error in computed Darcy-Weisbach friction factor versus discharge

Dispersion

Four measures of longitudinal dispersion were determined from dye curves (Table 9). In addition, a longitudinal dispersion coefficient was computed using Equation 11 and the mean depth, water surface slope, and flow cross-sectional area. All of the dispersion indicators with the exception of the measured dispersion coefficient (Equation 10) were highly correlated with each other (Table 9). Computed dispersion coefficients were within a factor of 2.3 of measured coefficients. The remaining discussion and analysis of dispersion focuses exclusively on the variance of time of travel because it is the most directly intuitive measure of physical habitat heterogeneity.

Travel time variance was inversely related to discharge (Figure 19). LWD effects on both friction factors and dispersion were most pronounced at low flow. Uncleared reaches provided considerably more heterogeneous conditions at low flow, but conditions for cleared and uncleared reaches converged at higher flows. At discharges above 350 cfs, travel time variance for cleared reaches (n = 4, mean = 29.6 min^2) was smaller than for uncleared reaches (n = 6, mean = 32.2 min^2), but the difference was not statistically significant (probability of t = 0.08 , confidence level = 92 percent). Not surprisingly, dispersion was directly related to channel roughness. Darcy-Weisbach friction factor was highly correlated with travel time variance (r = 0.77).

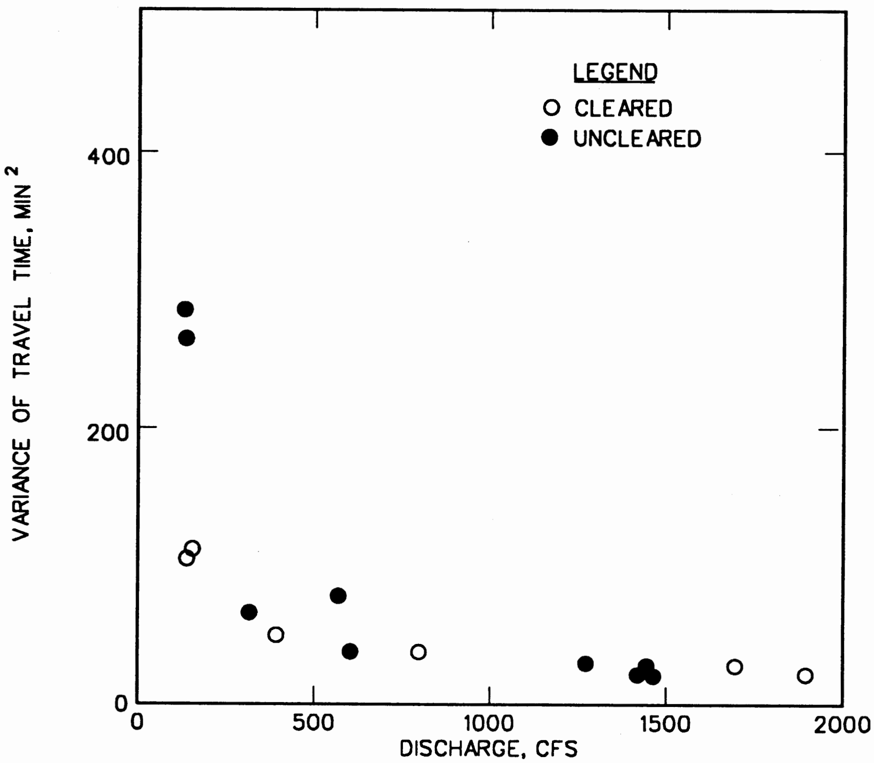


Figure 19. Dye test time-of-travel variance versus discharge

Physical Habitat

Transect data

Velocity (at 0.6 depth), depth, bed material type, and cover type were sampled at 3-ft intervals along transects spaced one channel width apart in representative segments of the study reaches. Six transects were sampled in each of the three study reaches in fall 1989. In May 1990, five transects were sampled in the cleared lower reach, and eight transects were sampled in the uncleared middle reach. Depth, velocity, and cover were sampled at 3-ft intervals along each transect. Bed material was sampled from the center of each transect in the lower reach, from points 25 and 75 percent across each transect in the middle reach, and at selected locations near and distant from LWD in the middle reach.

Graphical analysis. Transect depth and velocity measurements are plotted in Figures 20 and 21. Plots of depth for cross sections in cleared reaches are trapezoidal, and velocity patterns are symmetrical about the channel center line. In contrast, data from uncleared reaches show considerable lateral variation in depth and velocity and variation in width from section to section. Uncleared reaches provided considerably more area with relatively shallow depth and reduced velocity. Velocity data collected in May 1990 were interpolated into an array representing spatially equidistant values, and contours representing 1- and 2-fps isovels were plotted for the cleared and uncleared reaches (Figure 22). The geometric complexity of the regions of reduced velocity is evident from Figure 22. To better define regions of hydraulic influence of LWD formations and to characterize habitats from which benthic macroinvertebrate samples were collected (Payne and Miller in preparation), additional depth-velocity transects were sampled in close proximity to several LWD formations in the uncleared middle reach in May 1990. Velocity patterns in channel segments dominating several ramp formations along the left descending bank and by a collapsed bridge are depicted in Figure 23.

Frequency distributions. Frequency histograms of the transect data indicated higher levels of habitat diversity in uncleared reaches (Figure 24). In general, the cleared reach contained less cover and had higher velocities than uncleared reaches. Low-velocity habitats and cover were in greater supply in uncleared reaches. In the fall, only 23 percent of the sampled points in the cleared reach had some type of cover, either small logs (11 percent) or undercut banks (12 percent), while 56 percent of the points in the uncleared reaches had some type of cover (small logs, logjams, undercut banks, or canopy). Only 22 percent of the points in the cleared reach had velocities less than 1 fps, while 55 percent of the points in the uncleared reaches had velocities less than 1 fps. Stages and discharges were higher in the spring, obscuring cover. Only 8 and 32 percent of the points in the cleared and uncleared reaches, respectively, had cover. The influence of LWD on velocity patterns remained strong, however, as 19 and 40 percent of the points in the cleared and uncleared reaches had velocities less than 1 fps, respectively.

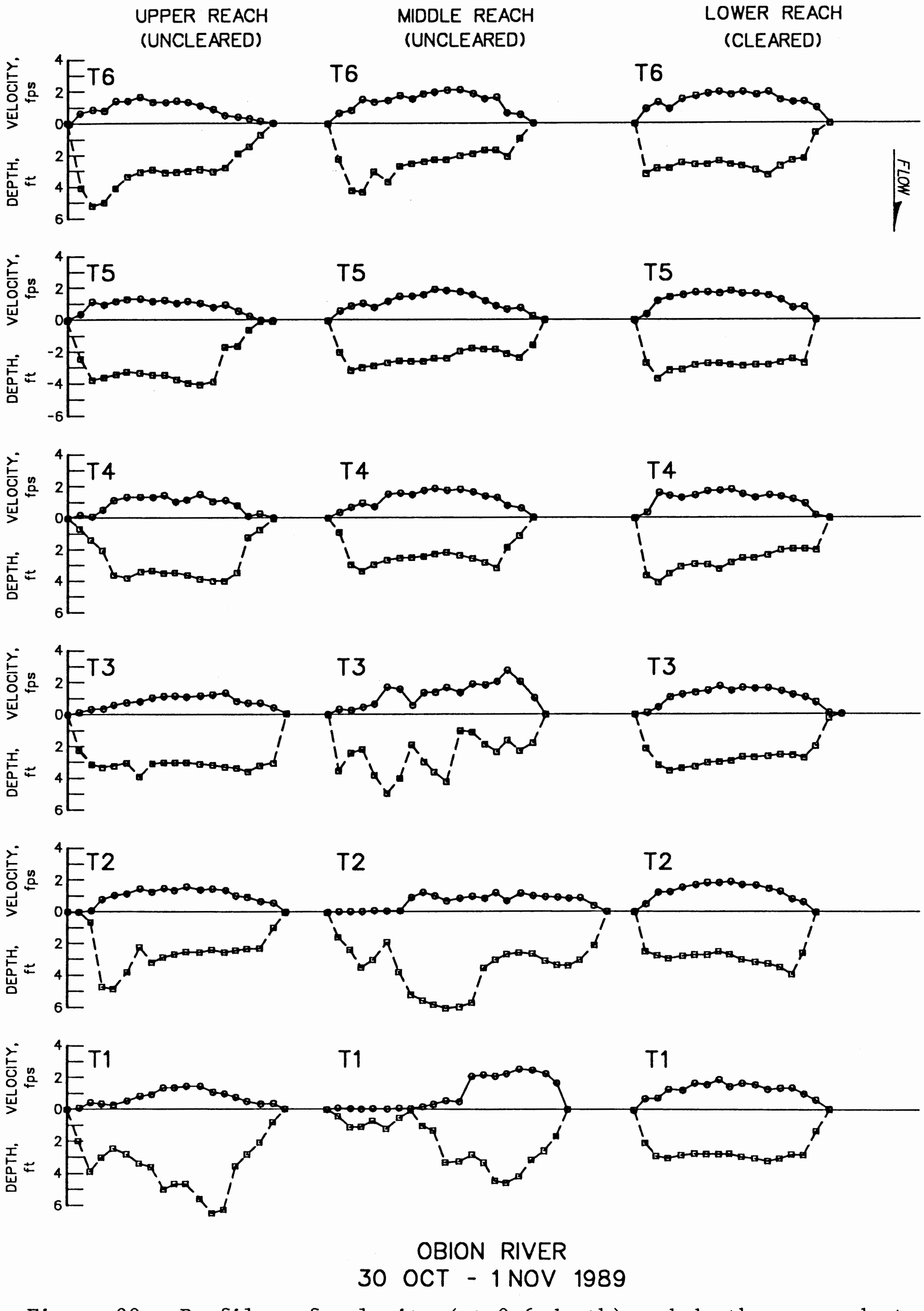


Figure 20. Profiles of velocity (at 0.6 depth) and depth measured at 3-ft intervals at cross sections spaced one channel width apart in the upper, middle, and lower reaches, fall 1989

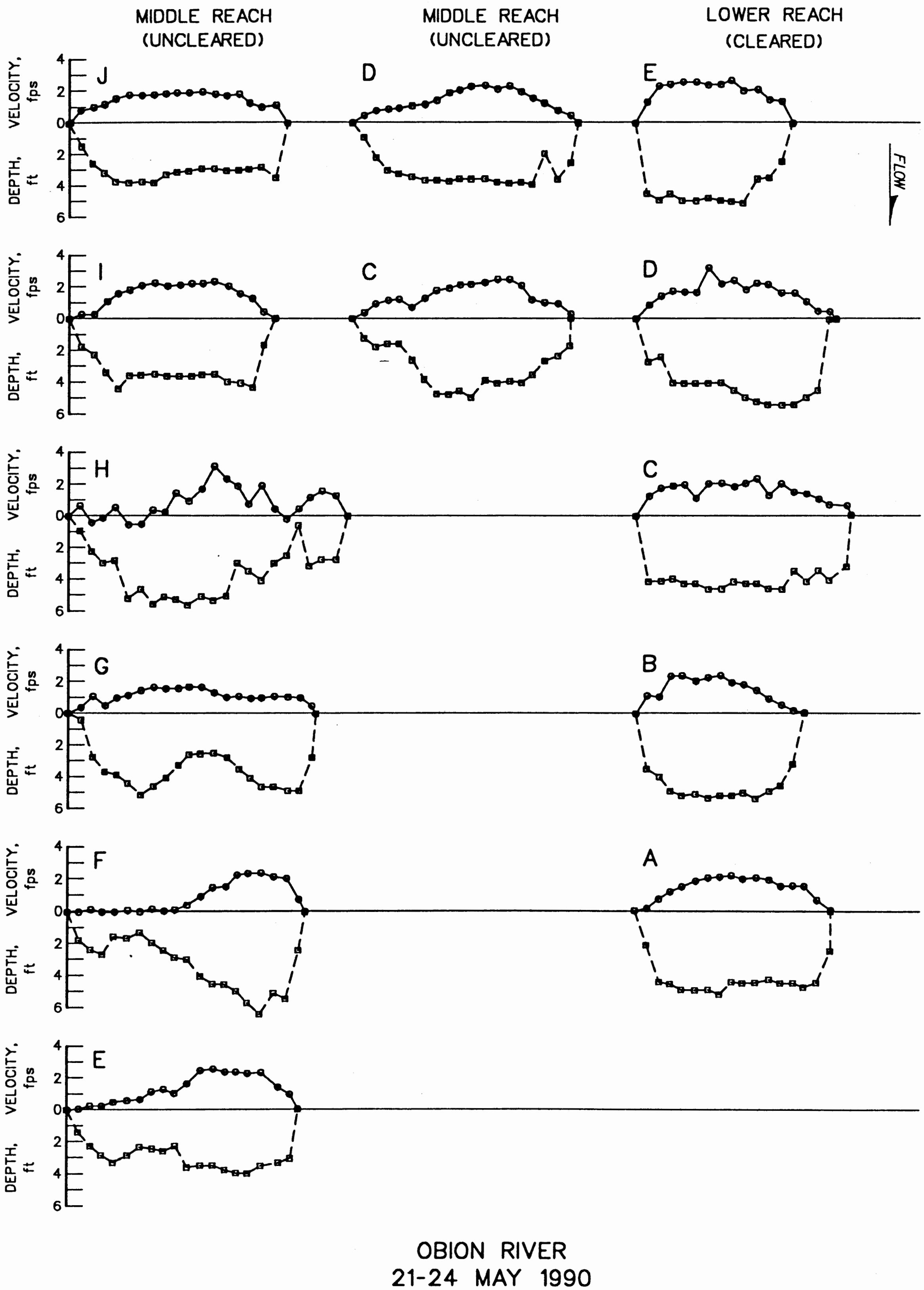


Figure 21. Velocity (at 0.6 depth) and depth measures at 3-ft intervals at cross sections spaced one channel width apart in the middle reach and five transects within the lower reach, spring 1990

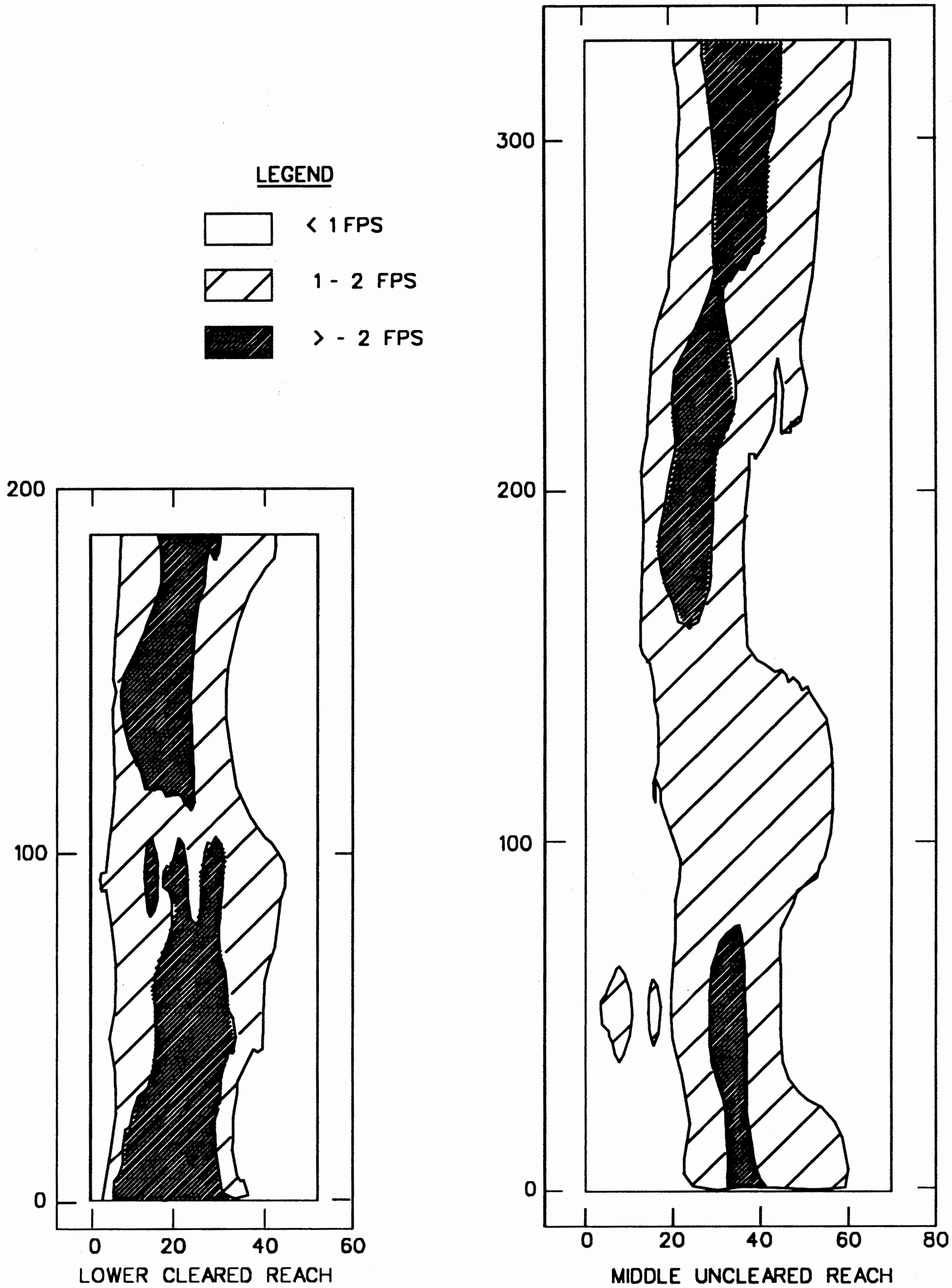


Figure 22. Velocity patterns in cleared and uncleared reaches, 21-24 May 1990. Flow is from top to bottom. Coordinates on x-axes represent distances in feet from right descending bank while y-coordinates are distances along a channel from an arbitrary baseline

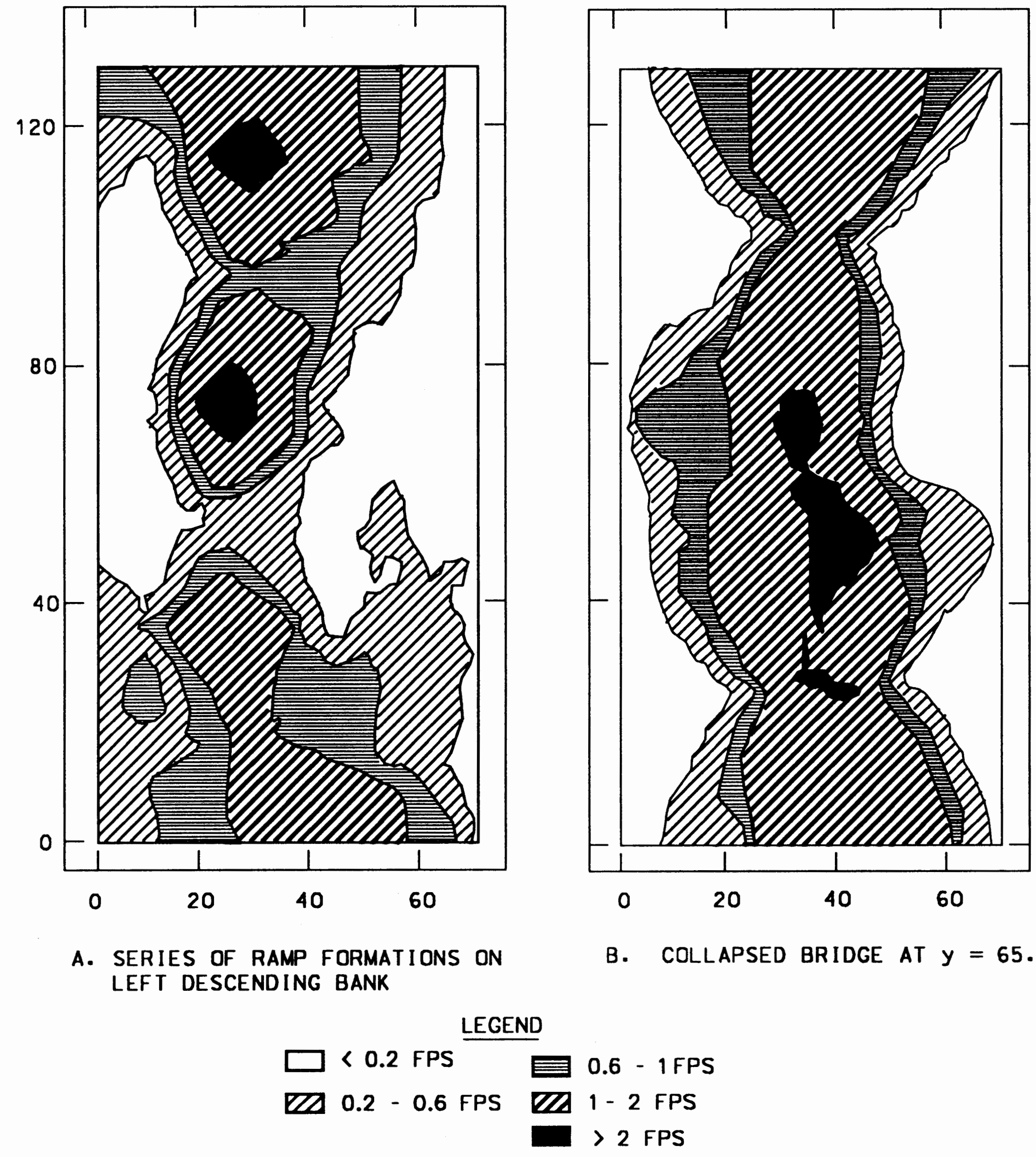
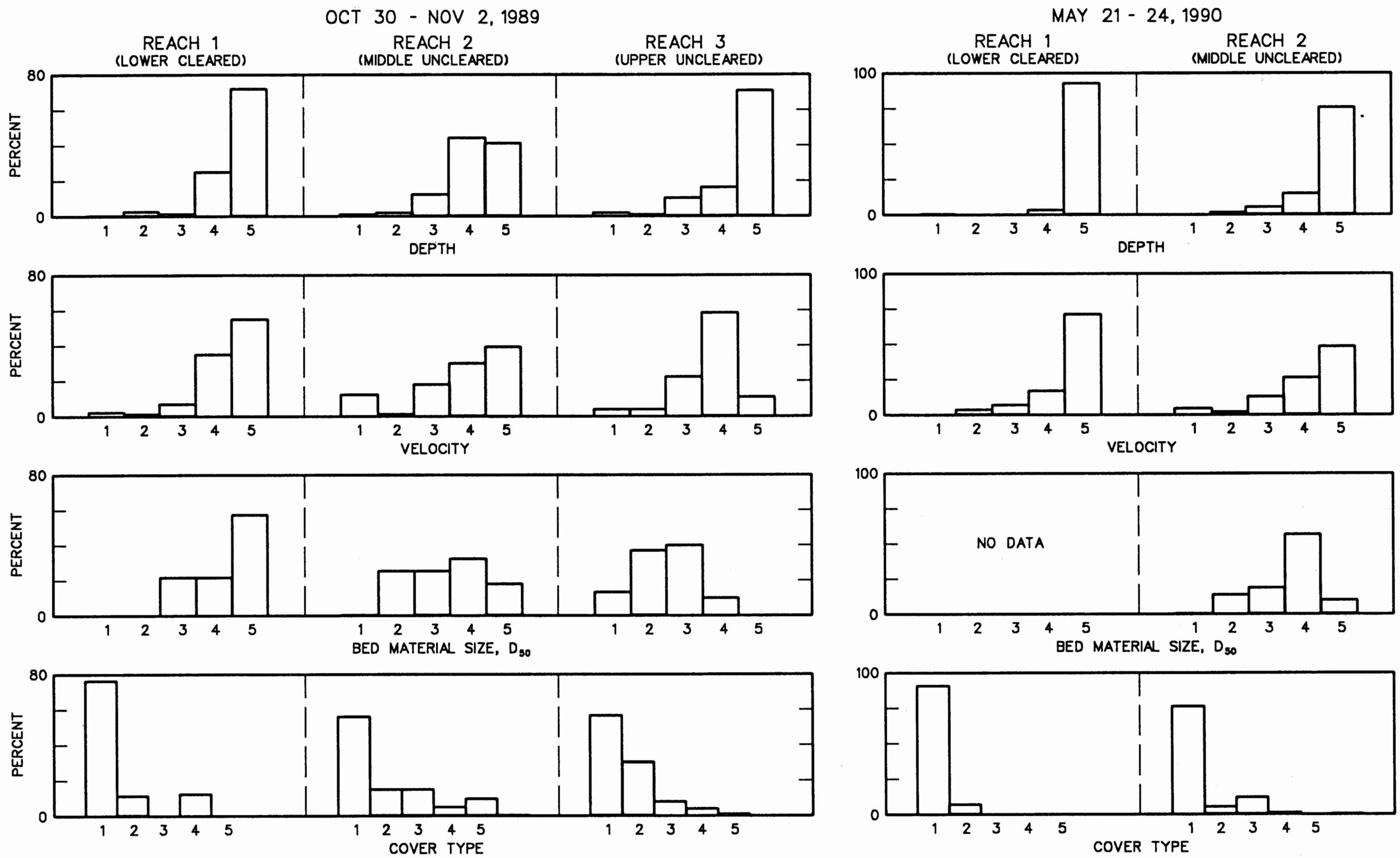


Figure 23. Velocity patterns in short segments of uncleared middle reach, 23-24 May 1990. Flow is from top to bottom. Coordinates on x-axes represent distances in feet from right descending bank while y-coordinates are distances along a channel from an arbitrary baseline



LEGEND

BAR NUMBERS →	1	2	3	4	5
DEPTH, cm — RANGES	0 TO 5	5 TO 20	20 TO 50	50 TO 80	> 80
VELOCITY, cm/s — RANGES	0 TO 1	1 TO 5	5 TO 20	20 TO 40	> 40
D_{50}, mm — RANGES	0 TO 0.065	0.065 TO 0.30	0.30 TO 0.40	0.40 TO 0.60	> 0.60
COVER TYPE	NONE	SMALL LOG	LOG JAM	UNDERCUT BANK	CANOPY

Figure 24. Frequency histograms of depth, velocity, bed-material size, and cover type for data collected at 3-ft intervals along transects spaced a channel width apart

Statistics. Summary statistics for the transect data indicated that the cleared lower reach was generally deeper and swifter than uncleared reaches (Table 10). Depths and velocities were subjected to two-way ANOVA using reaches and cover classifications as treatments (Table 11). Two cover classifications were used, these being cover and no cover. Variation in depth and velocity because of reach and cover were statistically significant at the 99.99 percent confidence level. However, variations in depth and velocity because of interaction of reach and cover classification were not statistically significant, indicating that the local physical effects of remnant LWD in cleared reaches were similar to the local effects of LWD formations in uncleared reaches. Evidently microhabitats 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.

Diversity indices

Shannon diversity indices (Table 12) were calculated for depth, velocity, and bed type for each of the three reaches for the fall 1989 data. Because bed type classifications were not made in the lower cleared reach during the spring of 1990, Shannon indices were also calculated using only velocity and depth for comparison (Table 12). Fall indices were higher than spring indices, presumably because of higher spring stages. Shannon indices indicated higher levels of physical habitat diversity associated with LWD. Fall indices for uncleared reaches averaged 29 percent higher than for cleared reaches. The spring index for the uncleared reach was 80 percent higher than for the cleared reach.

Physical habitat diversity was also quantified by counting the number of different composite scores recorded for each subreach. This quantity, termed "habitat richness," is found in parentheses in Table 12. Habitat richness values for uncleared reaches based on depth, velocity, and bed type averaged 21 out of a possible maximum of 125, while cleared reach richness was only 13. Similar values based on depth and velocity were 14 out of a possible maximum of 25 for uncleared reaches but only 9 for cleared reaches.

Bed composition

Bed material in all three reaches was sand but was finer in the uncleared reaches and at sampling points adjacent to LWD (Table 10). Bed sediment samples collected in May 1990 were analyzed for organic content (combustible matter) as well as grain-size distribution (Table 13). Combustible

Table 11

Two-Way ANOVA Results

Significance Level of F Statistic*

Descriptor	Depth	Velocity	D_{50}**
		Fall	
Reaches	0.0066	<0.0001	<0.0001
Cover	<0.0001	<0.0001	0.0129
Interaction	0.0584	0.9606	0.5410
		Spring	
Reaches	<0.0001	0.0001	0.1398
Cover	<0.0001	0.0008	0.4844
Interaction	0.7160	0.0978	--

* The significance level is the probability that the observed differences are due to chance.

** Spring bed samples were not collected concurrently with systematic cover sampling. Therefore, spring D_{50} statistics are from single classification ANOVA.

Table 12

Shannon Diversity Indices

(Habitat Richness)*

Reach	Fall 1989**	Fall 1989†	Spring 1990**
Lower cleared	1.73(13)	1.60(11)	1.03(7)
Middle uncleared	2.46(20)	2.17(15)	1.88(14)
Upper uncleared	1.99(21)	1.74(13)	--

* Shannon indices were computed using Equations 13 and 14. Habitat richness in the number of different composite scores (Equation 13) observed at the specified time and location.

** Based on depth, velocity, substrate, and cover.

† Based on depth, velocity, and cover.

Table 13

Bed Sediment Composition, May 1990

Descriptor	Mean [SD]		
	D_{50}, mm	Percent Finer Than Sand	Percent Organic Matter
Cleared reach	0.57 [0.08]	1.20 [0.45]	1.31 [0.40]
Uncleared reach	0.44 [0.18]	4.83 [11.58]	1.11 [0.75]
Points w/o cover	0.50 [0.12]	3.37 [3.38]	1.24 [0.50]
Points w/cover	0.32 [0.04]	5.24 [2.42]	2.16 [3.85]

Means for cleared and uncleared reaches were not significantly different. (ANOVA $p > 0.13$ for all three variables). Means for points with and without cover were not significantly different except for percent organic matter ($p = 0.0025$).

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 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 percent), but this was partially due to a single sample from the uncleared reach with an extremely high fine content (51 percent). Sediment samples collected from sampling points stabilized by LWD, formations ("with cover," Table 13) had lower mean D_{50} values and higher percentages of organic matter and fine material. Combustible matter content was positively correlated with median grain size ($r^2 = 0.342$, $p = 0.0001$), but not percent fines ($r^2 = 0.016$, $p = 0.46$).

PART IV: DISCUSSION OF RESULTS

LWD densities for the South Fork Obion River, Tennessee, ranged from about 0.0004 ft^{-1} to about 0.004 ft^{-1}. The ratio of LWD volume to water volume ranged from 0.006 for a recently cleared reach to a maximum of 0.087. Selective removal of LWD reduced LWD density by 50 to 90 percent, depending on the method used to determine density (Table 5). Although the method of measuring LWD density used in this study was crude, the resulting values were reasonable in light of data presented by earlier reports.

a. Zimmer and Bachman (1976) reported averages of 11.8 and 19.7 LWD formations per mile for six prairie and four woodland streams in Iowa with drainage areas ranging from 146 to 329 square miles and an average slope of 4.07 ft/mile. The LWD formations were counted at low flow. Data in Table 3 for uncleared reaches at low stage (study numbers 8 and 16) indicated 68.5 and 61.2 LWD formations per mile exclusive of streambank trees.

b. Hortle and Lake (1982) reported dimensionless LWD densities of 0 to 0.233 for the Bunyip River in Victoria, Australia (drainage area = 280 square miles; width ranged from 14 to 40 ft), which compares to values of 0.006 to 0.09 for the South Fork Obion River presented in Table 3. Maximum values provided by Hortle and Lake (1982) may be larger because they sampled much shorter (165-ft) reaches.

c. Wallace and Benke (1984) reported a dimensionless LWD density of 0.0056 for Black Creek, a Georgia coastal plain stream smaller than the South Fork Obion River. The LWD volume was based on measuring individual stem diameters of all LWD located along selected transects within the study reach using snorkeling equipment. Stream widths and depths in the South Fork Obion River study area were approximately twice those of Black Creek; reach lengths were about 1.5 times as long. Considering the differences in stream dimensions and measurement techniques used in both studies, the difference in reported values appears to be reasonable.

d. Petryk and Bosmajian (1975) computed vegetation densities using Manning's n values measured by Ramser (1929). Computed densities ranged from 0.028 to 0.035 ft^{-1} for a straight channel with maximum flow depths of 4 to 9 ft, average widths of 70 to 210 ft, and water surface slopes of 0.00042 to 0.00059. The channel was "badly obstructed by trees 2 to 12 inches in diameter covering side slopes, except intervals aggregating half length of right bank occupied by large weeds and bushy willows." Vegetation had summer foliage, and three-fourths of the length of the channel bottom was covered with short nonwoody vegetation. The photograph of the channel indicates that vegetation density due to streambank trees was much higher than that for the South Fork Obion River study site.

e. Hauer (1989) reported values for the volume of wood per unit area of stream bottom for two streams in the South Carolina coastal plain. Meyer's Branch, an undisturbed reference stream, had a mean value of 0.0353 ft^3/ft^2, and Steel Creek, a nearby stream recovering from flow augmentation due to thermal discharges, had a mean value of 0.000623 ft^3/ft^2. Meyer's Branch values were comparable to Wallace and Benke's (1984) data (0.0371 ft^3/ft^2) for Black Creek, Georgia. Robison and Beschta (1990) reported an average value of 0.06 ft^3/ft^2 for five undisturbed Alaskan streams based on measurements similar to those of Wallace and Benke (1984). Computed values for the South Fork Obion River, Tennessee, varied from 0.03 to 0.11 ft^3/ft^2 for the cleared reaches and 0.14 to 0.31 ft^3/ft^2 for the uncleared reaches. Because previous investigators measured and computed volumes for each piece of LWD or for each formation, the differences in reported values and those reported here for the South Fork Obion River appear to be reasonable and can probably be attributed to the difference in measurement techniques used.

Hydraulic Resistance

Techniques currently employed for determining hydraulic effects of LWD removal rely on estimation and engineering judgment (Barnes 1967, Chow 1959). Engineers select friction factors based on experience or by comparing the channel in question to photographs or tabular descriptions in standard references such as Barnes or Chow. These photographs generally depict channels with virtually no LWD or channels with evidently high (but unspecified) LWD densities. Reported friction factors for badly obstructed channels are three to four times larger than those containing less LWD (Shields and Nunnally 1984). Few actual observations of friction factor before and after LWD removal are available; reported reductions range from 10 to 80 percent (Gippel 1989; U.S. Engineer Office, Mobile, Alabama 1940). Using current approaches, an engineer analyzing likely effects of using the aforementioned selected LWD removal guidelines on the hydraulic roughness of a given channel reach can do little more than guess.

Measured friction factors

Measured Darcy-Weisbach friction factors ranged from 0.08 to 0.51 and were smaller for higher discharges. Decreasing flow resistance with increasing stage and discharge (within-bank flows) is in agreement with observations of Manning's n for larger sand-bed rivers (Chow 1959), similar channels in the southeastern United States (Fasken 1963), and other channels with significant LWD (Gippel 1989; Gregory, Gurnell, and Hill 1985). 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, Gilman, and Newsom (1979) reported a hundred-fold decrease in Darcy's *f* for a hundred-fold increase in discharge for a small steep English stream.

The effects of LWD on *f* were most pronounced at low flow. LWD appears to promote 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. Similar observations were reported by Hecht and Woyshner (1987) for Manning's n values for the Pajaro River in California.

At higher flows (>350 cfs), the mean value of *f* for cleared reaches was 0.11, which compares to a value of 0.17 for uncleared reaches at similar discharges. However, this difference may decline with time. Inspection of cleared reaches following storms revealed additional LWD either from riparian trees falling into the channel or exposed in the bed as a result of scour. Although investigation of effects of LWD 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 provided by Simon and Woodside (undated) (discussed above) suggested that LWD removal may have triggered or exacerbated bed lowering through the upper portion of the study area. Similar observations have been reported by others (Bilby 1984, Strom 1950 in Gippel 1989). These results suggest that flood control benefits of LWD removal may be extremely limited in channels similar to the one studied.

<u>Computed friction factors</u>

The procedure to compute friction factors described above may be adapted to estimate effects of LWD removal on channel roughness. However, the accuracy of predicted friction factors will be greater if LWD counts are made at extremely low stage when LWD formations are mostly above water. Additional modifications should be made to the procedure to address site-specific conditions. For example, grain and form roughness may be predicted using different methods from those used herein. Allowances should be made for bends in meandering channels. Accuracy will be greatest when users have applied the procedure several times and have gained familiarity with the channel system and the procedure.

A step-by-step approach for estimating LWD removal effects on bank-full channel roughness is as follows:

<u>a</u>. <u>Step 1.</u> Walk or float the reach of interest at extreme low stage, and complete the form in Appendix C by placing a check mark in the

appropriate block for each LWD formation that would influence a bank-full flow. Reaches longer than 1 mile may be subdivided into shorter segments.

b. Step 2. Compute LWD density DA using Equation 1.

c. Step 3. Compute the ratio K_d/L using Equation 20.

d. Step 4. Compute the friction factor due to LWD f_d using Equation 19 and the estimated reach-mean hydraulic radius for bank-full discharge.

e. Step 5. Compute the roughness due to the bed (form and grain roughness) f_b using an appropriate technique such as those discussed by Miller and Wenzel (1985). Performance of the technique in streams with similar bed material and channel size should be considered.

f. Step 6. Compute total roughness as the sum of f_d and f_b plus additional roughness due to bends or structures. This total roughness will be for the channel in an "as-is" condition.

g. Step 7. Compute roughness for bank-full flow after LWD removal by completing the form in Appendix C and omitting or modifying entries as appropriate. Then repeat Steps 2-6.

Physical Habitat

Selective removal of LWD from the South Fork Obion River had definite effects on physical aquatic habitat, particularly at low flow. In general, many of the intuitive suggestions by earlier workers (Marzolf 1978, Yorke 1978) were confirmed. Cleared reaches had greater depths, higher velocities, slightly coarser bed material, and were more uniform. Habitat area with velocity (at 0.6 depth) less than 1 fps was reduced by about 50 percent; cover was reduced by 50 to 75 percent; and flow heterogeneity as measured by travel time variance was reduced by 65 percent at low flow but was relatively unchanged for high flows. Habitat diversity as measured by the Shannon function was reduced by 30 to 80 percent. Microhabitats adjacent to remnant LWD formations in cleared reaches were similar to those adjacent to LWD in uncleared reaches, although far less abundant. Areas adjacent to LWD (within or closer than 15 cm to LWD formations) tended to be shallower and have lower velocities and finer bed material with more organic matter. Cover reduction may be the most important factor in regard to fish populations (Angermeier and Karr 1984, Gore and Johnson 1980, Hickman 1975, Hortle and Lake 1983), while loss of LWD surfaces used as substrate is likely to be the most important factor for macroinvertebrates (Benke et al. 1985).

These results were slightly different from 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 LWD removal decreased rather than increased depth. Results herein were similar to those of Hauer (1989), who observed higher current velocities (20 to 30 percent) and lower levels of benthic organic matter (50 to 97 percent) in a South Carolina stream without significant LWD compared to a reference stream with LWD. Results described above for travel time variance confirmed work by Gregory, Gurnell, and Hill (1985), who found travel time for hydrograph peaks in a small English stream was affected by the presence of LWD at low flow, but had little effect on travel time at high flow.

PART V: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

LWD plays an important role as a component of aquatic habitat. Although LWD enters food webs as it decays, the major importance of debris lies in its structural characteristics and the way it influences channel flow patterns. Physical processes associated with debris in streams include the formation of pools and retention of fine sediment and organic matter.

Awareness of the adverse effects of complete LWD removal on channel stability and aquatic habitat has led to the development of guidelines for selective removal of LWD as a means of balancing habitat and conveyance objectives. These guidelines (Appendix A) involve the use of manual labor and small equipment to remove only the LWD that causes significant flow obstruction. Removal of bank vegetation and disturbance to stream habitats is minimized. Personnel within some Corps districts have already completed or are in the process of classifying the streams under their jurisdiction according to these guidelines. Use of these guidelines for project planning and design requires quantification of the hydraulic and environmental impacts of incremental LWD removal.

In this study, a simple method for quantifying LWD density and computing associated friction factors was developed and tested using data collected during an LWD removal project on the South Fork Obion River in western Tennessee. Physical conditions of both cleared and uncleared stream reaches were measured by collecting three types of data: LWD density, dye tracer tests (for computing reach mean hydraulic parameters), and physical habitat (depth, velocity, bed type, and cover) at selected transects. The LWD density was the important independent variable, while the dye tracer and physical habitat data were used to study macroscale and microscale effects of LWD, respectively. Macroinvertebrate samples were also collected at low flow conditions, and the results are presented in a companion report to this study (Payne and Miller in preparation).

Conclusions

Removal of LWD from the study reach decreased near-bank-full friction factor by about one third. 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. Benefits of proposed LWD removal projects should be carefully analyzed in light of costs and environmental impacts. Findings of this study generally agreed with work by others in different types of streams. The simple procedure developed in this study for quantifying LWD density and its effect on channel resistance may be used for environmental impact assessment and hydraulic engineering analyses. Considerable refinement and site-specific adaptation may be in order, however. The method for prediction of channel roughness coefficients does not account for local losses because of bends or flow expansion and contraction at bridges, debris dams, or riffles.

Recommendations

To refine the methodology used in this study, additional data should be collected from two more stream LWD removal projects. Streams with higher LWD density and different types of bed sediment from that encountered in this study would be preferable. Physical data should be collected over a range of flows varying from normal low-flow to bank-full conditions. Concurrent biological data should be collected at base flow. Data should be collected to document preproject and postproject conditions. Investigation of additional methods of determining LWD density, such as using video recorders or low altitude aerial photography to count and measure the LWD formations, is recommended.

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APPENDIX A: FUNCTIONS OF LWD IN RIVERS

Quantification of LWD

Definition

Platts et al. (1987)* defined LWD as material greater than 1 m in length and with a diameter at one end greater than 10 cm. They also listed three other commonly used categories to classify organic debris: (a) coarse woody debris, which includes material smaller than LWD but larger than 1.0 mm in diameter, (b) fine particulate organic matter between 0.45 and 1.0 mm in diameter, and (c) dissolved organic matter less than 0.45 mm in diameter. Keller and Swanson (1979) defined LWD as logs, limbs, and root wads greater than 10 cm in diameter. Andrus, Long, and Froehlich (1988) used the same definition but additionally specified a minimum length of 1 m. Wallace and Benke (1984) imposed no lower limit on their definition of LWD. The difficulty in specifying a minimum diameter is that the significance of LWD is dependent upon stream size. Smaller diameter material becomes less important with increased stream size. Additionally, LWD commonly occurs as accumulations of smaller pieces usually trapped on a large tree; these accumulations are often referred to as "formations." In such cases, the overall size of the formation is of primary importance.

Measurement

The irregularity of LWD makes absolute measurement very labor-intensive. The LWD density in streams varies widely but tends to be higher in lower order streams. Wallace and Benke (1984) measured the diameter of all stems intersecting a line transect to compute wood volume and surface area per area of channel bottom. Ward and Aumen (1986) measured the dimensions of each log individually. Lienkaemper and Swanson (1986) measured top and bottom diameters of logs and used the formula for the frustum of a paraboloid (excluding the root wad) to calculate volume.

Platts et al. (1987) provided a summary of various methods used to measure and map organic debris. These include percentage area of streambed affected, counts of individual pieces or accumulations, direct measurement to estimate volume or biomass, and measurement of the effect on the channel.

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* References cited in this appendix are included with those following the main text of this report.

Measurements can also be made of the location and orientation of individual pieces.

Mass or volume of debris per unit bed area is the most quoted index of LWD quantity found in the literature. Mass calculations are based on dry specific gravity of wood. Wallace and Benke (1984) found that LWD was preferentially located near the erosional bank, and most of it was submerged. Because buried wood is never measured, and submerged wood is often ignored due to difficulties in field measurement, estimated values of LWD quantity may often be low. No single "best" method of LWD qualification exists. Methods should be selected to match the study objectives, given the temporal and fiscal constraints.

Geomorphic Significance of LWD

LWD provides storage for sediment and acts as a buffer that regulates bedload transport (Beschta and Platts 1986). Several studies (e.g., Beschta 1979, Bilby 1984) have reported that sediment export markedly increased after LWD removal. Because turbulence generated by flows in contact with LWD dissipates considerable energy, LWD removal will usually result in channel scour (Heede 1981). Gippel (1989) noted that scour following removal of LWD from rivers in the State of Victoria, Australia, often exposed underlying layers of LWD. The presence of LWD also influences overbank deposition because of the backwater effect from the accumulations causing local channel avulsion.

The geomorphic role of LWD depends on its size relative to channel dimensions. LWD can cause considerable variation in channel width. Upstream from LWD, channels tend to widen and decrease in depth because water is diverted around the obstruction. When LWD spans the channel but is not in contact with the bed, flow may converge under a log to produce local scour and channel narrowing. Pools are more common in streams containing LWD. Major LWD formations are important determinants of channel morphology and probably the main trigger for channel adjustments. They can create shoals, dam sloughs, and lakes; cause large side jams; and completely block the channel.

Depending upon location (i.e., proximity to bank), orientation, and stability, LWD can have either a positive or an adverse effect upon bank stability. Stability of LWD is influenced by a number of factors (Keller and Tally 1979). Often a large part of the mass of the LWD rests outside the channel. The root wad may be anchored to the bank, contain soil, and, thus, be quite dense. After initial rotation, branches are sometimes buried by bed sediments, and, especially in the case of willows, fallen trees may continue to grow and bind the accumulation. Cherry and Beschta (1989) conducted a flume study using wooden dowels to simulate the hydraulic behavior of individual logs in channels. They noted that upstream orientations caused major flow disturbances, produced relatively large scour depths, and appeared to increase the potential for streambank erosion because the flow was deflected toward the sides. More stable positions (with respect to streambank erosion) would be orientations downstream or perpendicular to the flow. However, the perpendicular orientation generally produced the most local scour.

Storage of Sediment and Organic Material

Accumulations of LWD create important storage areas for inorganic sediment and organic material. The stability and storage capacity of debris is enhanced by the presence of branches and roots, which help to anchor the debris and serve as a matrix to trap and consolidate sediment and fine particulate organic matter. Sediment deposits formed upstream from debris accumulations serve several important functions for fish populations including food production sites, formation of spawning riffles, and retention of fine sediment. Storage of fine sediment and organic matter behind large debris or accumulations of smaller debris significantly delays the transport of this material downstream (Marston 1982) and enhances retention and uptake of nutrients (Munn and Meyer 1990). Further evidence for the role of debris in sediment storage has come from debris dam removal studies (Heede 1985, MacDonald and Keller 1983) in which sediment and organic matter transport rates increased severalfold after debris dams were removed from stream channels. The chief benefit of the sediment storage capacity of debris to fish habitat appears to be the moderating influence of debris on sediment transport rates, the effect of which is to buffer the channel against rapid changes in sediment loading that could degrade spawning beds, fill rearing pools, and reduce invertebrate populations.

Hydrologic Significance of LWD

Justification of LWD removal is sometimes based upon the claim that a significant reduction in channel roughness will increase the flow velocity, consequently reducing the duration as well as frequency of overbank flooding (Graf 1980, Nunnally 1978). However, few scientific studies have been made to substantiate this claim. In fact, depending upon the spacing and size of tributary streams, the change in travel time as a result of the change in velocity associated with LWD removal could possibly result in higher flood peaks at some locations on the main river (Gippel 1989). One difficulty in isolating the effects of LWD removal based upon historic flow records is that land-use changes within the watershed, which affect the rainfall/runoff process, may have been occurring during the same time period. In general, LWD significantly reduces reach mean low-flow velocity and increases reach mean depth. However, high flows at near-bank-full conditions tend to drown out the influence of LWD. When extremely large LWD accumulations (i.e., debris dams) collapse during a flood, the resulting hydrograph will be modified by pulse of flow unrelated to rainfall.

The hydrologic effect of LWD removal is greatest for flows that are confined within the stream channel banks. Removal is important when near-bank-full flow conditions occur frequently. Larger floods will still overtop the banks regardless of the amount of LWD in the channel. However, for these high out-of-bank flows, LWD removal may cause a rapid decrease in the duration and extent of floodplain inundation (Gippel 1989).

Hydraulic Significance of LWD

A comprehensive study of the hydraulic effects of LWD removal has not been documented, and verified hydraulic simulations of LWD removal effects were not found in the literature. However, some investigators have reported on the effect of LWD on channel roughness, the effect of obstructions on velocity distribution and water surface profile, and laboratory studies using various contrived roughness elements or obstructions. Some of these studies and data have previously been summarized (Gippel 1989, Shields and Nunnally 1984) and provide a basis for comparison. Reported reductions of roughness coefficients following LWD removal range from 10 to 80 percent (Gippel 1989; U.S. Engineer Office, Mobile 1940). However, regrowth of vegetation and trees on cleared channel sides and top banks can significantly increase the resistance factor within one or two growing seasons. Therefore, estimation of roughness values should include consideration of regrowth potential and maintenance schedules.

At present, engineers typically estimate the effects of LWD removal on stages by manipulating the resistance factor (Manning's n or Darcy f) in the uniform flow equation. Equations for resistance factors are suitable only for computing resistance due to roughness elements that are small relative to flow depth; thus, selection of resistance factor values for complex natural channels with LWD is an art based on judgment and experience. Most engineers use tables of typical composite factor values and photographs of example reaches where resistance factor has been previously measured for some specific flow event. A portion of these measurements relates to changes in the resistance due to the type and amount of vegetation or obstructions in the channel. The approach normally taken when using these tables and photographs is to select a basic resistance factor (Manning's n) for a straight, uniform channel (e.g., 0.025 to 0.035) and then increase this value for each of the additional factors that are present which influence the roughness (Chow 1959, Fasken 1963). Of the eight factors identified by Chow (1959), three are influenced by LWD removal, these being vegetation, channel irregularity (removal of sediment bars), and obstruction to flow. Channels obstructed by LWD can have Manning's n values as high as 0.15 (Chow 1959).

Most previous experimental and theoretical studies of resistance to flow in rivers have concentrated on small-scale roughness where the size of the roughness element size is small with respect to flow depth. LWD is an example of large-scale roughness for which skin friction is relatively unimportant (Petryk and Bosmajian 1975). Studies of large-scale roughness have considered boulders (Bathurst 1985), cylinders (Li and Shen 1973), artificial strips (Knight and MacDonald 1979), vertical vegetation (Dawson 1988), etc.; however, LWD has received little attention. Petryk and Bosmajian (1975) presented a formula for computing resistance factors for heavily vegetated channels that includes a term for vegetation density (defined as the ratio of the sum of vertical plane plant cross-sectional area to the product of reach length times mean flow cross-sectional area). Use of the formula requires direct or indirect determination of the vegetation density and its variation with depth. This report presents a technique for estimating the vegetation density term as a result of LWD.

Hydraulic effects of LWD vary with flow depth. When the diameter of single logs or vertical dimension of LWD accumulations is large compared to flow depth, the roughness coefficient may be abnormally high. At high flows, LWD becomes deeply submerged and exerts less influence on flow hydraulics.

Similarly, roughness generally decreases as the channel increases in size in the downstream direction. For a channel heavily obstructed with LWD (e.g., a forested floodplain), Petryk and Bosmajian (1975) predicted that vegetation density increased slightly with depth of flow, resulting in an increasing resistance value with discharge. The approach for computing resistance factors presented in this report at least partially accounts for effects of depth variation.

Habitat Formation and Channel Geometry

Perhaps one of the most important functions of LWD with respect to habitat is the creation of pools (Bisson et al. 1987). Pools have lower current velocities and greater depths than runs and ripples and are attractive to most stream fishes. In small streams, single pieces of large debris or accumulations of smaller pieces anchored by a large piece often create a stepped longitudinal profile consisting of an upstream sediment deposit, the debris structure, and a downstream plunge pool (Keller and Swanson 1979). Size and location of pools are strongly influenced by debris position. The size of a single log or accumulation of logs spanning the channel can affect the size of the associated pool. Bilby (1985) showed that pool area was positively correlated with the volume of debris that anchored the pool. Many pools, however, are not created by scouring action of flow along the channel thalweg, but rather by eddies behind debris and other structures located at the channel margin. These pools, often called "backwater" or "eddy pools," are common features of all streams (Bisson et al. 1987).

By obstructing flow, LWD increases the complexity of stream habitats. Logs extending partly across the channel deflect the current laterally, causing it to converge and diverge. Even where the stream is too wide to permit logs to span the main channel, debris accumulations can promote formation of mid-channel bars and secondary channel systems (Harvey, Watson, and Schumm 1988). Debris, therefore, maintains physical habitat diversity by (a) anchoring the position of pools along the thalweg, (b) creating zones of reduced velocity along the stream margin, (c) causing lateral migration of the channel and the formation of secondary channel systems in alluvial valley floors, and (d) increasing depth variability (Bisson et al. 1987).

Biological Functions and Processes

Fine organic material stored by woody debris is considered to be a more important energy source for benthic invertebrates in streams than the wood itself (Hauer 1989), although certain invertebrates are specialized for processing raw wood (Anderson et al. 1978). A rich and diverse biological community has evolved to process this organic matter, and a detritus-based invertebrate community is believed to be the principal food resource of various fish populations. Invertebrates living directly on the surface of large debris also contribute directly to the food resources of fish. In sandy streams in the midwestern and southern United States, debris surfaces provide stable substrates that support a significant portion of the invertebrates eaten by warmwater fishes (Angermeier and Karr 1984, Benke et al. 1985).

The importance of woody debris as cover structure for fishes is well documented (Angermeier and Karr 1984; Harmon et al. 1986; Hickman 1975; Hortle and Lake 1983; Sedell, Swanson, and Gregory 1985). In addition to creating and maintaining pools, debris provides breaks in the current that serve as foraging sites for fishes feeding on drifting food items and also forms eddies where food organisms are concentrated. Provision of shelter during episodes of high flow is now recognized as a major cover function of woody debris (Bisson et al. 1987). The role of woody debris in supplying protection to aquatic organisms from aquatic or terrestrial predators has often been inferred but has not been quantified.

APPENDIX B: BEST MANAGEMENT PRACTICES (BMPs) FOR SELECTIVE CLEARING AND SNAGGING*

Trees and brush that shade streams and stabilize the banks should not be disturbed. In new channel construction, existing trees and brush should be left in place along the tops of banks. No stream work, including bank clearing and excavation or removal of materials, "snags," or other channel obstructions, should be allowed except at specific locations where significant blockages in streams occur. Channel excavation and snag removal should be accomplished with the minimum streambank clearing needed to provide access to the stream and should not be undertaken unless it is absolutely necessary. The following BMPs prescribe the manner in which snag removal and stream channel clearing should be undertaken:

a. Practices for snagging.

(1) Logjam removal. Only those log accumulations that are obstructing flows to a degree that results in flooding or significant ponding or sediment deposition should be removed.

(2) Removal of other logs.

- Affixed logs. Isolated or single logs should not be disturbed if they are embedded, jammed, rooted, or waterlogged in the channel or the floodplain, if they are not subject to displacement by current, and if they are not presently blocking flows. Generally, embedded logs that are parallel to the channel are not considered to cause blockage problems and should not be removed. Affixed logs that are crossways to the flow of waters in the channel and are trapping debris to the extent that could result in significant flooding or sedimentation may be removed.
- Free logs. All logs that are not rooted, embedded, jammed, or sufficiently waterlogged to resist movement by stream currents may be removed from the channel.

(3) Protecting riparian vegetation. No rooted trees, whether alive or dead, should be cut unless:

- They are leaning over the channel at an angle greater than 30 deg of vertical and they are dead or severely undercut, or damaged root systems are relying upon adjacent vegetation for support and it appears they will fall into the channel within 1 year and create blockage to flows; or
- Their removal from the floodplain is required to secure access for equipment to a point where a significant blockage has been selected for removal.

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* Source: State of New York (1986). The citation for this reference is included with those following the main text of this report.

Trees selected for removal should be cut well above the base, leaving the stump and roots undisturbed. Procedures for removing the felled portion should be the same as for other logs as discussed below.

(4) Equipment for log removal. First consideration should be given to the use of hand-operated equipment to remove log accumulations. When the use of hand-operated equipment is infeasible, vehicular equipment should be used in accordance with the following guidelines:

- Water-based equipment (e.g., a crane or winch mounted on a small, shallow draft barge or other vessel) should be used for removing material from the stream. A small crawler tractor with winch or similar equipment may be used to remove debris from the channel to selected disposal points.
- When stream conditions are inadequate for the use of water-based equipment, the smallest feasible equipment with tracking systems that minimize ground disturbance should be specified for use. Larger equipment may be employed from nonwooded areas where cables could be stretched down to the channel to drag out materials to be removed.
- Access routes for equipment should be selected to minimize disturbance to existing floodplain vegetation, particularly in the riparian zone. Equipment should be selected which will require little or no tree removal in forested areas.

(5) Log disposal practices. All logs or trees designated for removal from a stream or floodplain should be removed or secured in such a manner as to preclude their reentry into the channel by floodwaters. Generally, they should be transported well away from the channel and floodway and positioned parallel to the stream channel so as to reduce flood flow impediment. When large numbers of logs are removed at one location (e.g., logjams), their use for firewood may be most appropriate. Burying of removed material should not be permitted.

b. Practices for stream channel clearing.

(1) Small debris accumulation. Small debris accumulations should be left undisturbed unless they are collected around a log or blockage that should be removed. (Small debris accumulations will not constitute a significant blockage to flows. Upon removal of logs and other blockages under these BMPs and the following completion of the project, the changed water velocities will remove and disperse these small debris accumulations so that no significant blockage of water flows will result.)

(2) Removal of sediment and soils. Major sediment plugs in the channel may be removed if they are presently blocking the channel to a degree that results in ponding and dispersed overland flow through poorly defined or nonexistent channels and, in the opinion of appropriate experts, will not be removed by natural stream or river forces after logs and other obstructions have been removed.

(3) Disposal of spoil material. Conventional excavating equipment may be required for sediment blockages. This equipment should be employed in a manner which will minimize environmental damages as follows:

- Access routes for equipment should be selected to minimize disturbance to existing floodplain vegetation, particularly in the riparian zone.
- Material disposal and necessary tree removal should be limited to one side of the original channel at any given location.
- To the maximum extent possible, excavating equipment should not be employed in the stream channel bed.
- Where feasible, excavated materials should be removed from the floodplain. If floodplain disposal is the only feasible alternative, the spoil material should be placed on the highest practical elevation and no material should be placed in any tributary or distributary channels which provide for ingress and egress of waters to and from the floodplain.
- No continuous spoil pile should be created. It is suggested that no pile exceed 50 ft in length or width and a gap of equal or greater length should be left between adjacent spoil piles.
- Spoil piles should be constructed as high as sediment properties allow.
- The placement of spoil material around the bases of mature trees should be avoided where possible.
- All disturbed areas should be reseeded or replanted with plant species which will stabilize soils and benefit fish and wildlife. Revegetation should be in accordance with County Soil and Water Conservation District recommendations.
- All disturbed areas should be reseeded or replanted with plant species which will stabilize soils and benefit fish and wildlife. Revegetation should be in accordance with County Soil and Water Conservation District recommendations.

APPENDIX C: LARGE WOODY DEBRIS FORMATION SURVEY

LARGE WOODY DEBRIS FORMATION SURVEY

STREAM NAME: ______________________________

REACH INFORMATION : ______________________________

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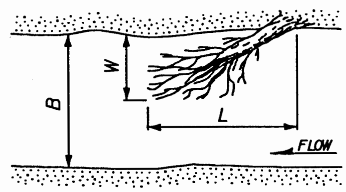
DATE: ____________________ TIME: ____________________

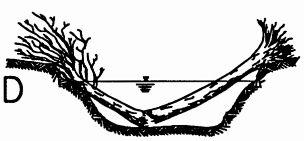


DIMENSIONS

LENGTH-PARALLEL TO FLOW DIRECTION \ WIDTH-PERPENDICULAR TO FLOW DIRECTION	W < B/4	B/4 ≤ W ≤ B/2	B/2 < W < B
L < B/2			
B/2 < L < B			
L > B			

TYPE A

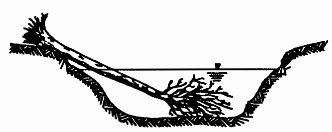
COLLAPSED BRIDGE



WIDTH-PERPENDICULAR TO FLOW DIRECTION	W < B/4	B/4 ≤ W ≤ B/2	B/2 < W < B

TYPE B

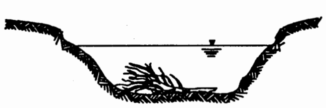
RAMP



LENGTH-PARALLEL TO FLOW DIRECTION			
L < B/2			
B/2 ≤ L ≤ B			
L > B			

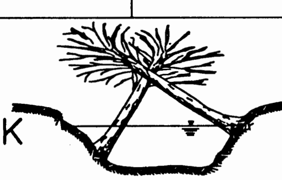
TYPE C

DRIFT



TYPE D

STREAMBANK TREES



Waterways Experiment Station Cataloging-in-Publication Data

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